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Composite Load Spectra for Select Space Propulsion Structural Components

Second Annual Report

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CONTENTS

CONTENTS

APPENDICES

iv

ILLUSTRATIONS

v

ILLUSTRATIONS

TABLES

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1.0 INTRODUCTION

1.1 <u>General</u>

Requirements for better performance and longer life have pushed engine designs to lighter weight systems, higher reliability, and increased pressures and environments. Temperatures, external and internal fluid flow noise, and mechanical vibration levels have increased markedly and have been shown to limit the hardware designs. Advanced engine concepts and designs are different enough that the loads cannot be simply scaled from other engines.

The use of engine cycles such as staged combustion on the SSME result in engine operating pressures in the 3000 to 7000 psi regime. High performance turbomachinery operate in the 30,000 to 100,000 RPM regime. These operational requirements result in complex high energy loading throughout the engine. The difficulty in installation, cost, and the potential for destroying an engine has severely limited the required instrumentation and measurements to adequately define loads of key components such as turbine blades. Also, accurate analytical methodologies for defining internal flow-related loads are just emerging for problems typically found in rocket engines. The difficulty of obtaining measured data and verified analysis methodologies has led to the probabilistic load definition approach of this contract.

Current loads analyses methodologies are driven by their usage in deterministic analysis methods. This includes strength and fatigue analysis as well as mechanical vibration. The deterministic solution typically uses an upper bound approach where maximum loads and minimum properties are used. For critical hardware, a separate sensitivity study is often made to determine more nominal operation and which loads and their variation govern the hardware design.

1

The Composite Loads Spectra Contract (CLS) and the associated Probabilistic Structural Analysis Method (PSAM) contract from Lewis Research Center are developing an integrated probabilistic approach to the structural problem. The probabilistic loads approach has the ability to more technically quantify knowledge relative to the loads. The use of mean values and distribution about this central value rather the maximum or enveloped loads can add greatly to the understanding of normal engine operation and still furnish as good or better knowledge of maximum conditions.

The present techniques often results in manufacturing of components that in many cases greatly exceed design requirements, but there is no way of assessing this margin for extending the useful life margin. Thus, to formulate more effective designs, it is necessary that the loads on the components of rocket engines be derived so that they can be applied by probabilistic analysis methods such as PSAM to end up with results that are quantifiable to more accurately reflect the true risk. The SSME engine is currently undergoing a failure modes affect analysis. The assessment would be much easier to perform if a probabilistic analysis and associated risk assessment were available.

This project will provide methods to combine technologies of analytical (deterministic) loads and probabilistic modeling. Since these methods will be developed from a generic approach, they will be applicable to current or advanced liquid rocket engine designs.

1.2 Project Objective

The objective of this program is to develop generic load models with multiple levels of progressive sophistication to simulate the composite (combined) load spectra that are induced in space propulsion system components, representative of Space Shuttle Main Engines (SSME), such as transfer ducts, turbine blades, and liquid oxygen (LOX) posts and system ducting. The approach will consist of using state-of-the-art probabilistic methods to describe the individual loading conditions and combinations of these loading conditions to synthesize the composite load spectra simulation.

2

The methodology required to combine the various individual load simulation models (hot-gas, dynamic, vibrations, instantaneous condition, centrifugal field, etc.) into composite load spectra simulation models will be developed under this program. Results obtained from these models will be compared with available numerical results, with the loads induced by the individual load simulation models, and with available structural analysis results from individual analyses and tests. These theories developed will be further validated with respect to level of sophistication and relative to predictive reliability and attendant level of confidence.

A computer code incorporating the various individual and composite load spectra models is being developed to construct the specific load model desired. The approach is to develop incremental versions of the code. Each code version will add sophistication to the component probabilistic load definition and the decision making processes, as well as installing a new set of loads for an additional component. This allows for ongoing evaluation and usage of the system by both Rocketdyne and NASA.

2.0 SUMMARY

2.1 General

The development of probabilistic generic load models is a 3-year base program and a 2-year option program. Rocketdyne is responsible for the overall project. Battelle Columbus Laboratories is the major subcontractor for developing probabilistic load models and furnishing technical expertise in probabilistic modeling in general.

The effort is divided into three tasks: the probabilistic model theory, code development, and code validation and verification. An initial survey effort was made to review available LOX/LH$_2$ data on the components under study and appropriate probabilistic load methodologies for use in this contract. Four rocket engine components, LOX posts, transfer ducts, turbine blades, and an engine system duct are being used as example components for the loads development. Examples of these components are shown in Figures 1-3. Figure 1 is a cross section of the SSME powerhead showing the LOX posts in the 3 combustors and the transfer ducts between the powerhead components as well as the standard instrumentation that is used for monitoring the engine. Figure 2 shows a typical turbopump with its two sets of turbine blades. Figure 3 is an overall SSME powerhead view where the system ducts are depicted. Of specific interest is the high pressure oxidizer turbopump discharge (HPOTPD) duct.

Simply stated, the goal of the composite load spectra project is to provide a tool to generate probabilistic based composite loads of a rocket engine design. These loads can be used to improve aspects of current deterministic analysis approaches or as input to a probabilistic analysis method such as PSAM. In the first year, an initial code was developed that had the essential features of the planned expert system and probabilistic loads. This code was limited in scope to steady state turbine blade load components.

STANDARD INSTRUMENTATION AVAILABLE ON POWERHEAD

OPB OX MN PR
OPB FL MN PR
OXIDIZER PREBURNER
HPOT TURB FLG RAD ACCEL
HPOP DS PR
OPB LNG ACC
MCC LNG ACCEL
MCC OXID INJ PR
HPOT TURB DIS PR
P/B PUMP AX & RAD ACCEL
HIGH PRESSURE OXIDIZER TURBOPUMP
FPB DOME LNG ACC
MCC FUEL INJ PR CORR
HPFT TURB DIS PR,T
FUEL PREBURNER
HPFT RAD ACCEL
HPFP RAD ACCEL

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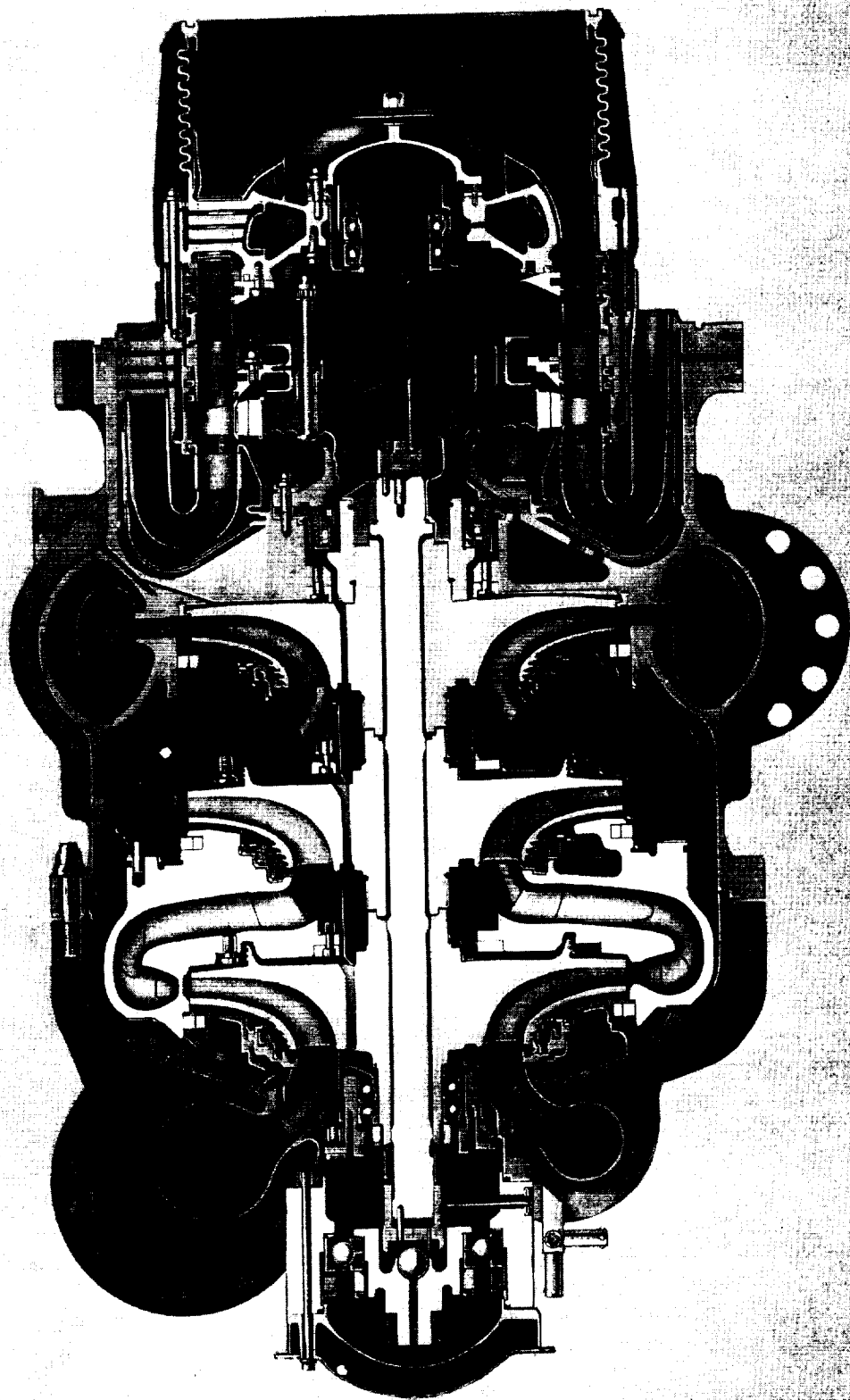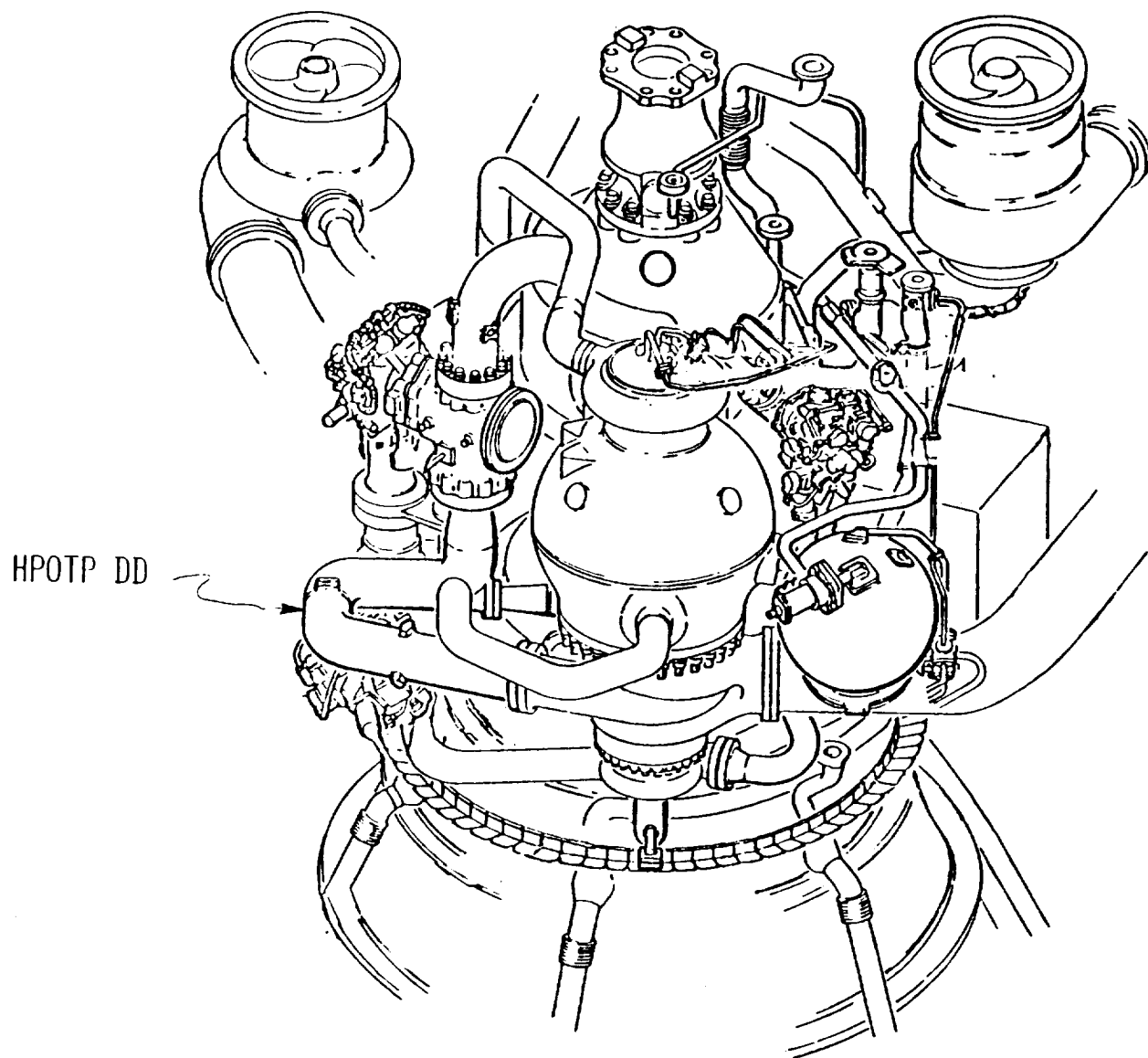
HPOTP DD

Figure 3. SSME Powerhead and Ducting

7

The four components utilized in this project and the individual loads considered are summarized in Table 1. The lox post, transfer duct and

INDIVIDUAL LOAD	TURBINE BLADE	TRANSFER DUCT	LOX POST	HPOTPDD	LOAD FORM
.STATIC PRESSURE	X	X	X	X	DUTY CYCLE*
.DYNAMIC PRESSURE					
.CHUGGING(TRANSIENT)	-	X	-	-	AMS, STATOS
.TURBULENCE					
.SINUSOIDAL					
(REPEATED PULSE)	X	X			AMS, PSD, STATOS
.RANDOM	-	X	X	X	AMS, PSD
.CENTRIFUGAL	X	-	-	-	DUTY CYCLE*
.TEMPERATURE	X	X	X	X	DUTY CYCLE*
.STRUCTURAL VIBRATION					
.TRANSIENT					
.SIDELOAD	-	X	X	X	AMS, STATOS
.POPS	-	X	X	-	AMS, STATOS
.STEADY STATE					
.SINE	-	X	X	X	AMS, PSD, STATOS
.RANDOM	-	X	X	X	AMS, STATOS
.DEBRIS	X	X	X	-	HISTORY
.RUBBING	X	-	-	-	EXPERT OPINION
.INSTALLATION	-	-	X	X	EXPERT OPINION
.FAB	X	X	X	X	
.FRICTION	X	X	X	-	PSEUDO LOADS
.TOLERANCES	X	X	X	X	

*LOW FREQ. & TRANSIENT

Table 1

Summary Matrix of Individual Loads vs Components

turbine blades were identified at the start of the project as specific components for load development. The fourth component chosen for this project was an engine system duct, the HPOTPD duct. The oxidizer ducting system on the SSME has experienced a series of problems related to flow vibration that were unexpected. High energy flow vibration environments and their application to hardware analysis have not been well developed to date. By choosing this component, additional load definitions will be developed to aid in understanding and minimizing potential problems in future rocket engine designs.

2.2 Probabilistic Loads Development

One of the goals of the program is to be able to address generic engines that may include different mission profiles or incorporate design changes. This requires that a robust and general probabilistic approach be adopted for inclusion in the expert system model. During the first year of the program, a survey was conducted to select these probabilistic models and the initial programming, debugging and shake-down analyses were performed. The second year of the program has been oriented towards refining the methodology, developing a database that can be used by both the probabilistic methodology as well as the expert system, including different functional forms for the load description, model verification and validation, and the generalization of the computer program system.

The probabilistic model has included three probabilistic methods: 1) a second statistical moment propagation method which assumes that all of the load variables and engine parameters are normally distributed, 2) a discrete probability method (RASCAL), and 3) Monte Carlo analysis. The moment propagation method, referred to as the Quick Look Model (QLM) provides a fast, efficient method for determining the composite load distribution if the basic distribution of variables are not severely skewed. The RASCAL method is a discrete method capable of handling standard distributional forms, e.g. normal, lognormal, Weibull, and so on, non-standard forms such as bi-modal, and provides a range of levels for accuracy. This method can also be used to perform importance sampling which can be used to examine regions of concern for the composite load even though such values are rare. Finally, Monte Carlo analysis is available so that classical confidence limits can be obtained to assess the accuracy of the composite load prediction.

All phases of the mission history profile are addressable by the probabilistic load model. Currently, each portion of the mission history is defined as transient, quasi-steady, or steady state phases. The transient phase is characterized by rapid changes in the amplitude of the individual loads and engine parameters.

9

The rapid changes allow the program to ignore small oscillations about the much larger load fluctuations. The uncertainty in the load enters from the variability in the peak load value and its time of occurrence. The quasi-steady phase is that portion of the mission where the nominal value of the load is slowly changing, and thus can be approximated by "staircase" type steady state steps. The steady state region is where the nominal values of all of the individual and composite loads are constants. Unlike the transient phase, both the quasi-steady and steady state phase do have fluctuations superimposed upon the nominal behavior. Additionally, each of these phases can have "spike" values superimposed which represent the occurrence of rare events.

The linking of these different mission phases has been completed. It has been demonstrated that for the cases where data have been available that a continuous, nominal behavior is achieved. In addition, the predicted variability and the measured variability are well within acceptable limits. Therefore, the extension of the model has proceeded to engines and mission definitions for which little or no data exist.

For the SSME engine, expert opinion data was obtained by Rocketdyne for those loads and engine parameters used in the model for which measurements were unavailable. Test runs of the probabilistic model with these data included were made and compared to measured composite load data. The results indicated that the variability in composite load type data was adequately predicted by the model. Some differences in the predictions and measurements have been found and will be further looked at as part of the validation phase of the work. Late in the year, some analyses were begun which examines other engine types. The approach for determining the mean and variability in the individual load parameters for engines for which no data exist is to scale them using the engine design parameters and table look-up values developed during the second year of effort. Further development and validation of these analyses will be performed during the third year of the program.

Documentation of the code, ANLOAD, has continued throughout the program. Periodically, new versions of the program are sent to Rocketdyne for incorporation into the expert code system. The code work to date has primarily addressed loads that are dependent on the overall engine performance and are directly relatable to the engine model and duty cycle. The next phase of the loads development will address the remaining loads, e.g. fluid and mechanical vibration environment, sideloads and shock, pops and chugs and debris loads. Specific modeling for each of the components will also be completed. Additional specific modeling of the four components is also required. Representative loads for each of the four components in the study will be used for the validation and verification of the code.

2.3 Load Expert System

The probabilistic loads model is implemented as part of an expert system. The expert system is a tool to generate and analyze composite loads of a rocket engine design and to supply these loads for use in either deterministic or probabilistic FE computer codes for performing structural analysis of engine components. The statistical information used in the expert system primary basis is SSME test results, but expert opinion and other available engine data are used when appropriate. The approach is to develop the knowledge base of an individual load formulation on a reasonable physical basis in as generic a sense as possible. Engine statistical data are part of the knowledge base and used where appropriate.

A knowledge-based system has the facility of building up a large domain knowledge base and maintaining a large amount of data. It has the capability to perform logical deduction and inferences and thus it can help users to make decisions and to solve problems. These characteristics allow one to build an expert system to simulate and perform the process of problem-solving by an expert in a particular problem domain.

The functions of this knowledge-based system are to manage the database, provide expert knowledge in generic probability loadings for rocket engine.

11

A FORTRAN based non-proprietary knowledge system development tool that can satisfy all the needs of this project is not available. Therefore, it was decided early that the knowledge system will be built to suit the need of this project.

A simple philosophy discovered by pioneering workers in the field is that the power of a knowledge base system is in its capability to have a vast amount of domain knowledge and not necessary to have a complex inferencing engine. Following this philosophy, the load expert system LDEXPT was built with a simple inference system. The expert system uses the ANLOAD module to perform probabilistic modeling and statistical analysis. To make knowledge representation more efficient for the load expert system, a database system was implemented. This database system facilitates the communication between the expert system and the knowledge base, helps to maintain data integrity and avoid data redundancy. The load expert system LDEXPT version 2.0 has all three elements in place. Its knowledge base has load information for SSME type engines, knowledge about the influence coefficient method based on engine performance analysis and initially the turbine blade load information and scaling model calculation.

The load expert system is a rule-based expert system. The inferences are carried out with rules. In the load expert system, the rules are modularized. Each module is designed to solve a particular problem or to perform a task. The load expert system LDEXPT version 2.0 has rule modules to calculate turbine blade loads using scaling model and generate engine dependent loads (e.g. HPFTP discharge pressure) using influence coefficient method. The rules designed so far are mostly related to process control and information retrieval. In the next development, rules to generate probability models for a complicated composite load spectra will be designed which will require more use of artificial intelligence.

The load expert system now has knowledge of the turbine blade loads for generating steady state and quasi-steady state load spectra. Additional load data on pressures and temperatures are ready for adding to the rules.

12

The transient loads, pops and chugs and vibration loads, etc. are being developed and will be implemented as soon as the model development is complete. Knowledge on the transfer duct has been collected and rules for transfer duct load calculations can now be developed. The other two components loads will follow.

The basic expert system components of the load expert system LDEXPT: the expert system driver, the database system, the FORTRAN data management system and the basic probabilistic modeling and statistics tool box are all in place, that is the main tasks of system development phase are complete in version 2.0 of the code. The next main task is the further development of applications of the expert system to the composite load spectra project.

3.0 ENGINE LOADS

3.1 Background

The individual loads applicable to the four components in this project are summarized in Table 1. These loads cover a major portion of the loading throughout a rocket engine and are an excellent representative set to develop into an engine loads expert system. Where applicable, the individual loads are modeled for the entire duty cycle.

The loads are essentially self-generated or induced loads except for steady state g-forces and gimbaling requirements during flight. This allows the engines to be readily separated from the vehicle loads analysis as a subsystem with specific requirements.

The vehicle design can be divided into conceptual, preliminary, detail and design verification phases. This is followed by flight support and possibly uprating and problem resolutions. During the conceptual and preliminary design phases of a vehicle, major decisions are reached that spawn requirements for engine design. Vehicle requirements often are related to load alleviation or preventative measures and performance requirements to optimize vehicle design with engine design. Examples are: 1) controlled thrust rise rate, 2) in flight load alleviation, 3) cutoff impulse requirements, 4) engine inlet operating pressures and temperatures, and engine gimbal angle and rate requirements. A description of the approach to deriving loads design criteria for the space shuttle and it's payload is given in Reference 1. The vehicle system requirements reduce to a set of engine loads and system requirements, Reference 2, that define limits and engine duty cycles that end up defining a part of the engine individual and composite loads. (Note: most of the examples in the discussion herein presented are related to the SSME, but it is appropriate to rocket engines from a generic standpoint.)

14

The basic engine duty cycle is controlled by engine thrust buildup limits, Figure 4, engine thrust decay limits, Figure 5, and overall flight requirements such as maximum operational power, throttling during maximum dynamic loads and throttling near the end of flight to maintain a maximum g-load limit, Figure 6. These and other engine requirements are used to develop engine configurations and models. The engine models furnish inter-related deterministic loads -- pressures, temperatures, vibration levels, etc., for major components such as inlet and outlet conditions for transfer ducts, preburners, injectors, and turbopumps, see Figure 7. These interface loads are used with deterministic models to evaluate loads on individual components like turbine blades transfer ducts, LOX posts, etc. For instance, the steady-state loads are used by the hydrodynamics specialists to determine loads across each turbine stage or blade. The heat transfer specialists use information from the same model results to determine blade temperatures. The dynamics experts use the model results to determine turbine blade dynamics. The structural and analysis experts use the model information and the input loads from the other experts to develop the total load and structural analysis.

Deterministic models of varying complexity are used in all analysis efforts. The steady-state engine simulation model can furnish discrete values at an operating point. The influence coefficients relate one or several engine parameters versus other parameters. Somewhat similar information can be determined from the engine transient simulation model.

Simulation models are formulated using generic engine process descriptions and constitutive equations and detailed tabulation of the propellant physical properties. The description of the basic processes of the system simulation involves all static and dynamic formulations (where applicable) that are considered of importance in accurately representing the overall behavior of the engine during start, mainstage control, and cutoff. The validity and veracity of these process descriptions in terms of their ability to describe the overall system behavior have been proven by correlation of simulation results with engine test results from previously developed rocket engines.

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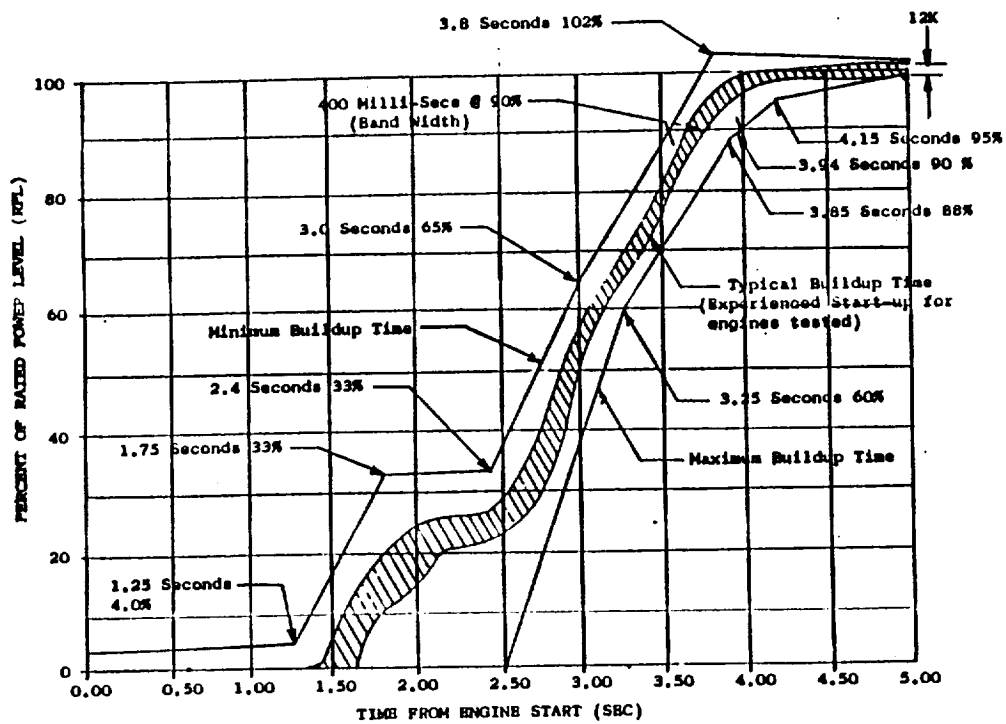
Figure 4. SSME Thrust Buildup Limits
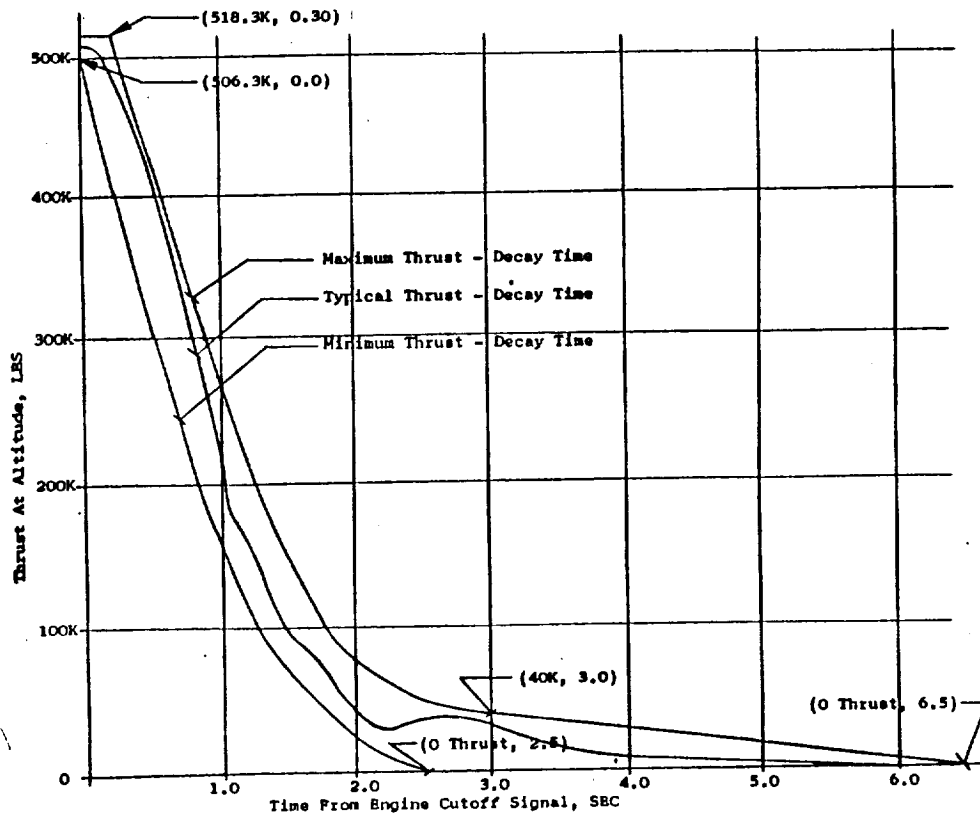
Figure 5. SSME Engine Shutdown Thrust Decay from FPL (Altitude)

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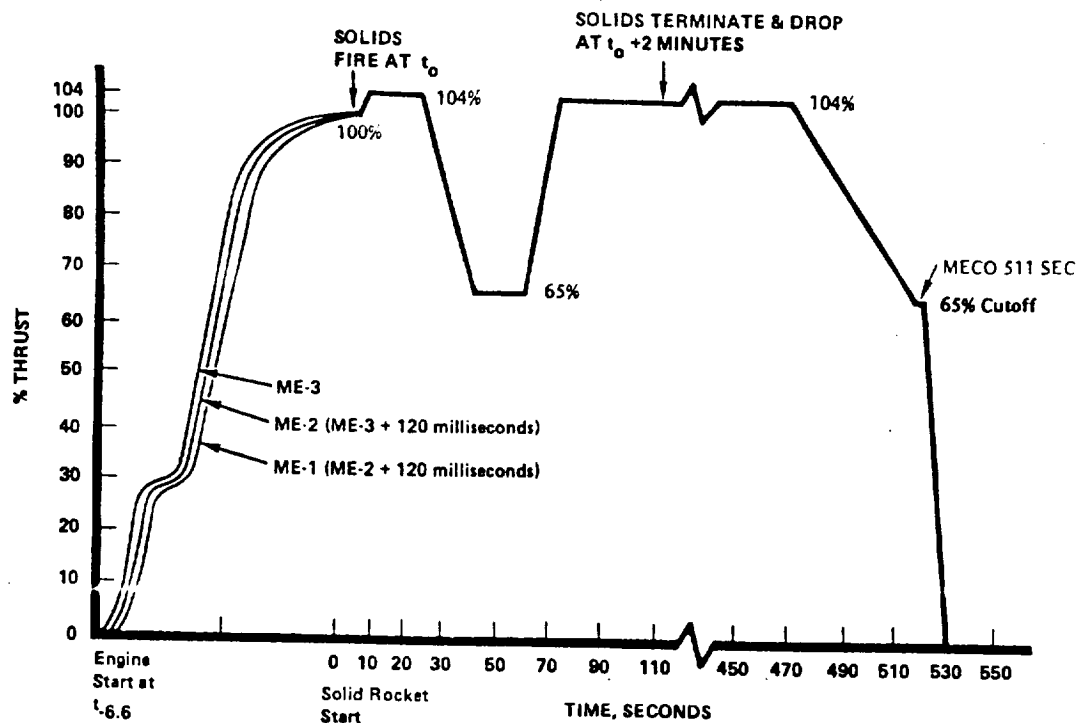
Figure 6. SSME Typical Flight Profile

With appropriately defined changes in the coefficients of the process descriptions, any new or modified engine component can be modeled into the simulation. Thus, the analytical description of even an entirely new engine system can be formulated and used with a confidence level that is based on previous proven performance of the analytic basis.

The engine performance model is a complex code not readily usable for the CLS effort. But engine influence coefficients are typically developed for rocket engines based on the performance model and are a practical method to develop a subset of the loads. Using an influence coefficient approach for the general operating conditions allows generic loads development across significantly different engine cycles. The three production LOX/LH_2 flight engines developed by NASA have had different engine cycles: the RL10 has an expander cycle, J-2 had a gas generator cycle and SSME has a staged combustion cycle.

17
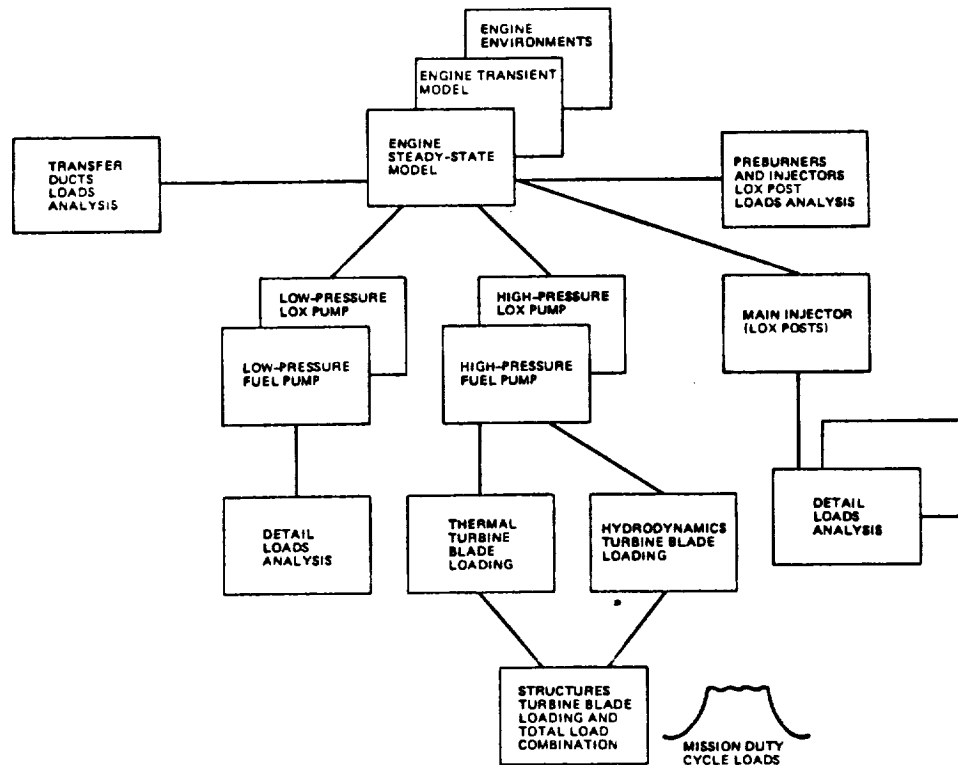
Figure 7. Interrelation of SSME Analysis Models

In support of this project, SSME influence coefficients have been extended to relate key engine variables to additional turbine and hot gas system related parameters. These coefficients are applicable to all four SSME components addressed by this project.

For the CLS work, the generic engine cycle is divided into start, cutoff, quasi-steady state and steady state operation. This operational mode will be discussed first.

3.2 Steady State and Quasi Steady State Operation

Except for transient conditions, nominal generic duty cycle loading can be described by a relatively few independent parameters -- the power level variation and other engine direct variables, such as inlet pressures and temperatures. Using these independent parameters with the applicable influence coefficient, nominal operation conditions are readily determined at component interfaces throughout the duty cycle.

Variations about the nominal condition for a specific load or parameter is approached in two separate methods -- one based on estimated engine random variation, and the other based on measured engine data. The estimated engine variation for selected independent variables (41 variables in the case of the SSME) can be used with the engine performance model to determine variations throughout the engine. These variations were developed from consultations with the individual experts on specific hardware and covers geometric, performance, etc. conditions that can effect the engine operation.

Typically, an engine performance data slice is obtained for each engine test and flight after the engine operation is stabilized and at a consistent time period, e.g. 190 to 200 seconds after start for the SSME. This information is utilized to calculate basic engine performance and the engine to engine and test to test variation of engine operation. Similar data is available for other engines such as the J-2, Atlas, F-1, etc.

The purpose of developing these variations is to furnish operating ranges for engine performance parameters and for use in validating the engine variations used in the model. These random variations are added to the predicted performance effects of direct independent variation allowed by specifications to determine parameter maximum and minimum expected values. The same percentage random variables are used throughout the thrust limits of the engine. The inherent assumption in this calculation of perturbed engine operations is that the 41 variables are independent random variables with normal distributions.

The basic perturbation technique of the engine model used for this analysis is similar to that used for calculating the influence coefficients that are being used for the Composite Loads Spectra (CLS) work. For the influence coefficients, a matrix of the individual effects are maintained to allow for direct determination of individual variable changes.

The measured engine data is only a small subset of calculated engine variables, but can be used to substantiate the calculated variations.

19

The 41 variables have counterparts, in general, to the 26 variables used in the engine influence coefficients. They are not identical since they are defined for different purposes. The 41 random variables as mentioned above are to cover all engine to engine and test to test variations for use in component design. The influence coefficients were developed for the customer's use in accounting for flight performance variations of a specific engine.

This information is the best data currently available for use on the CLS contract. Currently, there is ongoing work to develop a set of 2 sigma variations of measured parameters (two standard duration bounds) specifically based on the engine test database, but this will not be available for several months.

The direct independent variations include: propellant inlet temperatures and pressures, line resistance changes due to gimbaling, and tank repressurization flow settings. These maxima and minima define the operational limits used for engine component design. The engine ICD (Interface Control Document), e.g. Ref. 2, defines the required operational bounds of inlet pressures and temperatures that the engine must operate within. The gimbaling limits are also furnished in the ICD that were used to develop in-line resistance calculation input set. The effect of the direct variables are obtained by developing maximum non-compatible load variations based on the operational bounds -- the corners of the operational boxes. As mentioned above, these maximum non-compatible load variations are used as additions to the random variable perturbations to determine a maximum and minimum engine balance condition. Surge and transient effects are added as additional perturbation effects.

The random variable perturbation information is consistent with the CLS approach and has been used in the probabilistic load model development for ANLOAD. The direct independent variations are duty cycle load parameters along with power level that defines part of the component loads. The direct variations have nominal values and perturbations based on engine data -- see discussion in section "Comparison of ANLOAD Predictions with Expert Opinion".

The transient phase of the load definition is based on a combination of vehicle requirements, engine simulation models and engine test results. Typical vehicle requirements were discussed earlier -- start and cutoff transient envelopes specified to minimize vehicle loads. Additional requirements like rates of power level changes during throttling and associated up-thrusts are additional requirements that size control system variables. These system requirements indirectly control some of the nominal loads on components during transient operation. Thrust control drives pump speeds, torques, and system pressures and temperatures.

Various transient models are employed according to the type and range of the system dynamics under study. The analog model is generally used for surveying system characteristics, tradeoff and optimization of the control system, and in evaluating the large number of system changes typical of the early phase of engine design. Hybrid simulation is used to study digital control operation with the analog model. The hybrid computer thus simulates the role of an engine interfaced with a digital control system. The digital model, which most accurately represents system behavior, is used for simulation studies where maximum accuracy of results is needed, or where wide-range nonlinear operating conditions exceed the normal capabilities of analog simulation.

The dynamic simulation models and steady state performance models describe the same processes, but the performance models stress accuracy of steady state operation parameters, whereas the dynamic simulation models have to consider the overall system behavior throughout the duty cycle. From a loads definition standpoint on this project, the SSME dynamic digital simulation model results are used for transient conditions below 65% power level and performance model results above this thrust level.

The performance and dynamic simulation models are deterministic solutions. The transient solutions are essentially a nominal operation description of the engine operation. Engine to engine and test to test variation, as well as certain high frequency transient conditions or non-uniform flows and temperatures, are not adequately modeled for local load definition. Actual

21

engine measurements typically are not at the point of interest to define the transient and steady state operation conditions. Special instrumented components aid in this load definition, e.g. instrumented turbines. They may be close to the component in question, have better response characteristics, but usually survive or are utilized for a very limited number of tests. The definition of individual component load distributions require a combination of: 1) expert knowledge from previous engines and testing, special measurements, standard measurements and simulation models specifically formulated to calculate an engine test operation using measured conditions.

The hot gas transient load distributions have been based on the SSME HPFTP hot gas side of the engine. A simulation model was constructed of the fuel side where a combination of engine measurements and the simulation model were used to define hot gas system and fuel turbine start and cutoff transients. Measured parameters included pump speed, turbine discharge temperature, and pump delta pressures. Turbine torque was developed from pump head and torque curves with corrections for initial torque of the turbopump. The transient temperature ignition spikes were based on a correlation of instrumented turbine temperature measurements and the standard temperature discharge bulb measurement from measured data. After the temperature spikes subside, the turbine inlet temperature was based on measured discharge temperature corrected for the heat loss across the turbine due to the work energy extracted. Using this methodology, a series of engine tests were processed. The tests selected covered the expected bounds of the high pressure fuel turbine system operation. The results of this study was used in developing the transient model using this turbine as an example. A test by test tabulation of HPFTP turbine temperatures of all SSME hot fire tests and flights was also used in developing a statistical database of expected turbine temperature variation. The database included start transient temperature spikes as measured by the turbine discharge temperature. The magnitude of the inlet temperature spikes for the database tests was calculated using the same correlation procedure described above.

3.3 Structural Dynamic Excitation

The structural dynamic excitations used for rocket engine components are typically measured responses to combustion processes, turbomachinery generated loads or aerodynamic internal flows in ducts or nozzles. Accelerometers are located on external structure of major components that generate these loads such as the location(s) shown on the SSME main injector (the LOX dome interpropellant plate or the gimbal bearing flange connection and turbopumps, Figure 1). The accelerometers are standard measurements on test firings and engine flights. General vibration environments and engine redline limits are defined using the standard flight instrumentation. Additional accelerometer measurements are made for developing specific vibration environments to be used on individual components. The measured responses are used as dynamic base input accelerations for individual components like a LOX post or transfer duct, or as input accelerations to an injector assembly model with the entire set of LOX posts, interpropellant plate and LOX dome, etc. The current state of the art is to use the response as an input rather than transform the responses back to the actual load functions. Accelerometer data is measured in one, two, or three mutually orthogonal directions and furnish local magnitude and frequency. This data is insufficient to identify the various mode shape, so simplifying assumptions are typically made. These include independent assessment of vibrations by load direction and the assumption that there is no correlation between accelerometers.

The generic vibration mission-history-profile is complex since it can be made up of several different load components whose significance is variable and dependent on engine and component parameters (J-2, SSME, OTV, etc.). Pictorially, a typical vibration response mission-history-profile is shown in Figure 8. The loads can be categorized as:

1.   Transient Loads

   a.   Random pops (high frequency shock) - local combustion detonations during start and cutoff and up to minutes after cutoff. Pops can occur infrequently during the initial steady state condition.

23
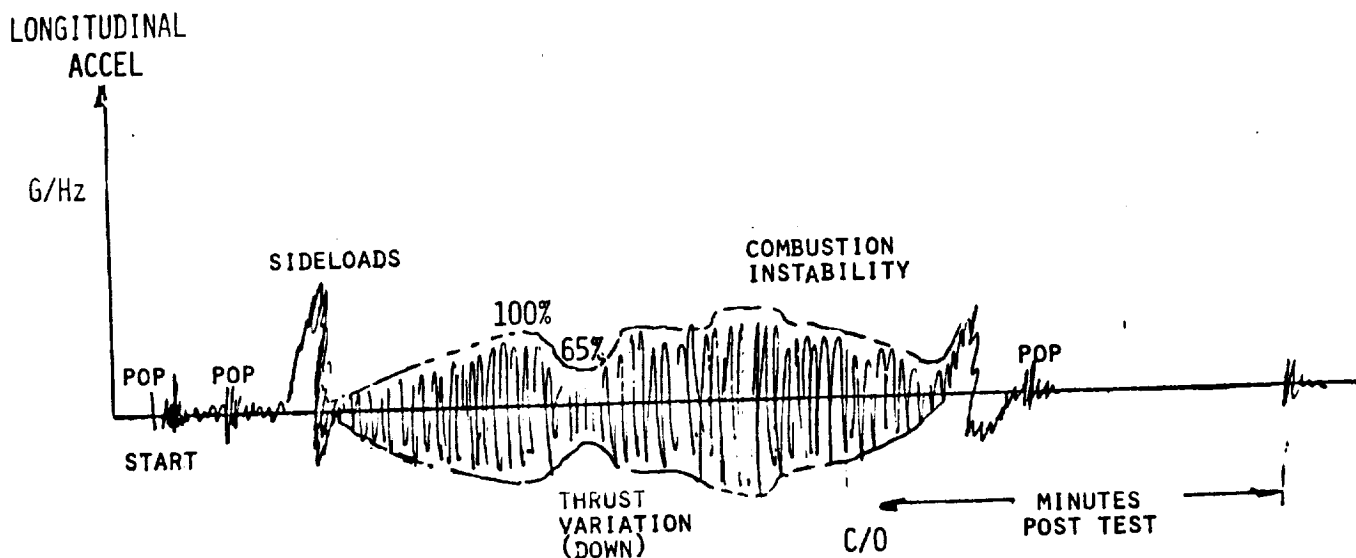
Figure 8. Pictoral Representation of Generic Vibration Response

b. Engine side load reactions (low frequency oscillations) - overall structural loading from the nozzle exhaust plume separation that is reacted by the primary load path through the engine structure and gimbal bearing and gimbal actuators.

c. Nominal vibration - energy that builds up with the magnitude of the combustion-related engine power level and flows in turbopumps. The vibration level varies as the engine power level is changed throughout the duty cycle.

2. Steady State Operation Loads

a. Nominal random vibration - combustion and turbomachinery related mainly from the load generator nearest the accelerometer, but potentially from other load generators on the engine.

b. Steady state sinusoidal vibration - significant discrete sinusoidal vibrations are measured at multiples of pump speeds on turbopump, preburner and main injector accelerometers.

The extensive engine test measurements have been taken with the standard accelerometers on virtually every engine test. The signals are processed with AMS/RMS, ISOPLOTS and STATOS records. Vibration levels and pops are tracked on a test-by-test basis.

Zonal shock and vibration criteria are defined for the entire engine. The methodology currently used for defining the loads envelopes the maximum responses from at least three tests each on two engines at the power level within a specified range (e.g., 65 to 109% PL). This is considered a 2 sigma (two standard deviation) response. The shock and vibration loads are used by dynamist as input to structural models.

NASA/MSFC uses similar techniques for developing random vibration criteria for the total launch vehicle. A discussion of this approach is found in Reference 5.

Chugs are another transient condition in the combustion process that are tracked along with the pops. Chugs are low level pressure oscillations whose responses on accelerometers would not be discernable. These oscillations are obtained from pressure transducer measurements. Chugs will be discussed along with the pops since they are both combustion stability type loads and are potentially dependent on each other.

An overall summary of the type of load, information base and typical limiting concern is listed in Table 2.

TABLE 2
PROBABILISTIC DYNAMIC LOADS

DYNAMIC LOAD CONSIDERED	INFORMATION BASE	DYNAMIC NATURE	LIMITING CONCERN	COMMENTS
Pops	Accelerometers OPB, FPB & gimbal bearing long./ start & cutoff STATOS	Transient detonation in ASI lox line or ASI cavity	Orifice deformation or ASI line rupture	Broad statos data-base of all engines/ duration of pop max. is ≤ 0.001 second
Chugs	OPB Pc & FPB Pc/ start & cutoff STATOS	Transient	None indicated	Duration, amplitude & chug frequency range identified
Side-Loads	Accelerometers OPB, FPB & gimbal bearing long.., & PBP radial/start & cutoff STATOS, shock spectrum data	Transient nozzle exit pressure fluctuation	Structural loads criteria document shock spectrum	STATOS are extensive on OPB, FPB & gimbal bearing long. accels limited data available PBP radial accels.
Steady State	All accelerometers AMS or composite & PSD plots	Engine mainstage	Structural loads criteria document steady-state vibration spec.	Extensive samples on all accelerometers.

26

3.4 Mechanical Vibration Loads – General Discussion

In a rocket engine there are two primary sources of energy which develop mechanical and flow vibration loads; these are the combustion process and turbomachinery. Rocket engine scaling methodology was developed by Barrett and reported in Reference 4. Barrett recognized four sources of excitations:

1. Mechanical energy from rocket engine fluctuations (i.e. combustion).
2. Acoustics from the rocket engine.
3. Aero loads from boundary layer fluctuations.
4. Self-generating machinery.

The acoustics and aero loads are primarily vehicle-related excitations, and the combustion and machinery loads are more engine-related.

Barrett's approach to defining scaling parameters is summarized as follows:

Any structural response possesses a vibration power, P_{vib}. Likewise, the impinging acoustic or flow loads can also be defined in terms of power, P_{mech}. The two can be related to a vibration efficiency factor, γ, as

$$\gamma = \frac{P_{vib}}{P_{mech}}$$

This relationship stipulates that a certain portion of the flow, acoustic, combustion and machinery power is transferred or absorbed by the component as vibrational power.

The mechanical vibration power can be expressed as

$$P_{vib} = \frac{1}{2\pi} \times \frac{\Delta f}{f} \times \frac{G^2}{cps} \times Wg$$

where W = the effective structural weight of the component

$\frac{G^2}{cps}$ = power spectral density (PSD) of the vibrating structure's acceleration

g = acceleration due to gravity

$\frac{\Delta f}{f}$ = effective bandwidth

The mechanical power is

$$P_{mech} = TV$$

where T is the thrust of the engine and V is the exhaust velocity of the rocket engine.

Substituting in these equations result in

$$\gamma = \frac{\Delta f W(G^2/cps)\,g}{2\pi f\,TV}$$

Assuming similar structures in different rocket engines possess similar dynamic characteristics, the mechanical efficiency factors are equal.

Therefore:

$$\frac{(G^2/cps)n}{(G^2/cps)r} = \frac{(\frac{TV}{W})_n}{(\frac{TV}{W})_r}$$

where r is the reference component, and n is the new component.

For the composite or sinusoidal case, the effective bandwidth cancels and

$$\frac{G_n}{G_r} = \sqrt{\frac{(\frac{TV}{W})_n}{(\frac{TV}{W})_r}}$$

A mass attenuation factor was also defined where an added mass, W_c, is mounted to structure where an environment was previously defined. Since the mechanical or acoustic forces driving the structure do not change, the amplitudes are decreased by a factor of

$$\frac{W}{W + W_c}$$

The above equation is then modified to:

$$\frac{G_n}{G_r} = \sqrt{(\frac{W}{TV_r}) \times \frac{(TV)_n}{W_n + W_c}}$$

where:

$$(\frac{W}{TV})_r$$

was assigned a constant value on the component type, and $W_n + W_c$ was the component weight and G_r is a PSD of normalized G_r vs frequency. PSD's are furnished for combustion chambers and turbopumps.

For example: For the combustion action

$$\frac{G_n}{G_r} = 7.6 \times 10^{-4} \sqrt{\frac{(TV)_n}{W_n + W_c}}$$

where W_n = combustion chamber + nozzle weights

where W_n = fuel + oxidizer weights.

29

The standard approach used by Barrett and still in use today was to define the environments by enveloping representative PSD data. Sinusoidal forcing functions were only generally addressed by Barrett.

The Barrett approach is somewhat a broad brush approach in that it only uses the gross engine thrust and exhaust gas, TV, as scaling variables for any engine forcing function. A more appropriate generic approach is to relate the power of each individual energy generating component, e.g. each combustor and each turbopump. For instance, the SSME has 7 primary sources of energy -- the 3 combustors - main injector/chamber/nozzle and two preburners, and four turbopumps - HPFTP, HPOTP, LDOP and LPFP. For the J-2 engine, there were two combustors - the main injector/chamber/nozzle and the GG, and the two separate turbopumps, LOX and fuel. For an engine like the F-1, the two turbopumps were mounted together with one turbine and constitute one turbopump assembly. With the above variations in engine components and related engine cycles, it is apparent that generic load definitions are best related to classes of components like combustors and variations of turbopumps rather than overall engine scaling. The TV parameter is inflexible to major engine configuration changes.

Combustor Loads.   The engine main injector/chamber/nozzle environment definition can be handled directly by Barrett's method in that essentially the total thrust and exhaust velocity are developed by these components. The preburners and gas generators, GG's, can be scaled similarly except the component injector pressure times area is the T, and the injector velocity is the V. Additional sinusoidal loads are superimposed on the random levels. These sinusoids are usually turbopump phenomena but can be a combustion instability phenomena.

Turbomachinery Loads. The turbomachinery loads are not as easily generalized. There are at least two primary load generators: the inertial unbalance loads from the turbopump rotor that are primarily related to one per rev loading and the flow "noise" loads. The 1/rev is primarily a sinusoidal response, whereas the flow noise is primarily a random response

plus sinusoidal response at multiples of pump speed. Other sinusoidal forcing functions can occur from items like bearing deterioration and rubbing. Therefore, the turbopump loads have both a random level and sinusoidal components. The sinusoidal components can be transmitted to other power generating components like combustors and can be an important part of their environment.

Current turbomachinery sinusoidal load correlation methods essentially use Barrett's procedure or pump speed squared, ω^2, as the scaling parameter for the composite response, G. The ω^2 can be related to both 1/rev rotor loads or flow noise response. So the ω^2 scaling can potentially be used for both sine and random response. Another approach is to use turbopump power (speed times torque) as a scaling parameter for a G^2 random response. This would be more in line with Barrett's power and efficiency factor concept. The 1/rev and flow noise loads related to flow interruption from vanes or impeller blades, etc., are primarily sinusoidal responses.

Vibration Loads - Generic Environment Definition

The vibration loads for engine components will be defined as both a composite and a PSD load function. The PSD will be separated into random levels and sinusoids.

Figure 9 summarizes the approach planned for developing the generic random vibration loads. One environment is planned for injector LOX post loading using the OPB accelerometer measurements. Another typical environment planned is a turbopump environment based on the PBP accelerometer. This response is typical of the input response applicable to the HPOTPDD.

- DEFINED AS PSD ENVIRONMENT

- SERIES OF SEGMENTS OF G^2 VS FREQUENCY
  - MEAN
  - COV
- VIBRATION LOADS ARE RESPONSES TO TWO BASIC GENERIC LOAD DRIVERS
  - COMBUSTION, I.E. OPB
  - TURBOMACHINERY, I.E. HPFTP
    - FLOW NOISE
    - UNBALANCE
    - POWER
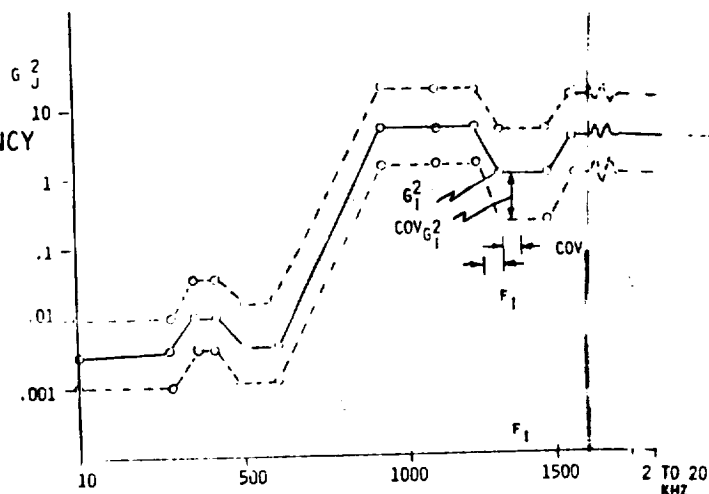
- DEFINE GENERIC ENVIRONMENTS FROM 109% P.L. AND R5 ENVIRONMENT
  - OPB
  - HPFTP

- USE BARRETT CRITERIA FOR BASELINE GENERIC COMBUSTION SCALING

  - $G^2 \rightarrow F \dfrac{(TV)}{W}$ T - THRUST
                           W - WEIGHT OF COMBUSTION COMPONENT
                           V - EXHAUST VELOCITY

  - MEAN VALUES OF G_I^2 SCALED

- FOR TURBOMACHINERY SCALING USE

- FREQUENCY VARIATION

  - COV_{FI} DETERMINED FROM OPB & FPB COMPARISON

  - NO SCALING OF F_I WITH POWER

- USE 26 TEST PHASE I ENGINE DATABASE FOR MEAN LEVEL AND FREQUENCY (G_I^2, F_I) BASIS

- USE R5 UPPER BOUND ENVIRONMENT WITH 26 TEST DATABASE MEAN TO

  - DEFINE 2σ & COV'S

  - ADJUST LOW FREQUENCY DC BIAS OF MEAN LEVEL

Figure 9. Generic Random Vibration Loads

The PSD is approximated by a piecewise linear, and its line segments are defined based on a mean and coefficient of variance (COV) for both the response level, G_i^2, and the frequency, F_i. The phase 1 engine 26 test data base will be used for defining (G_i^2, F_i^2) points using the OPB and PBP response accelerometers. The data has been processed so that a mean response level, rather than an envelop, can be defined. A 2σ bound of the response will be based on the current R5 envelop response for the measurements. The available processing of this data has an upper bound of 2500 Hz. Current plans are to reprocess the basic test data and expand the frequency band to 5000 Hz to be compatible with future processing of phase 2 engine data. More accurate measurements of a 2σ or COV response will also be available from this reprocessed data.

The approach for defining the sinusoidal environments is summarized in Figure 10. The same 26 test data base and R-5 environment limits will be used for their definition. A mean and COV is defined at each discrete sinusoidal response. The frequencies are correlated as a function of pump speed to allow for frequency shift with power level and for correlation with known geometric flow interruptions in the turbopump. The same two engine measurements OPB and PBP are used to give data consistent with the random response definition.

The response variation as a function of power level will be evaluated for both types of environments using a power level equivalent of Barrett's criteria and as a function of pump speed squares, ω^2, for the turbomachinery loads. These two approaches furnish different power scaling factors. Figure 11 furnishes an initial comparison of the two approaches and shows that ω^2 is essentially the power level raised to a 1.3 exponent, whereas the power function method is essentially linear with power level (thrust). The question of transmissibility of the turbopump generated sinusoidal responses needs further thought and development. Figure 12 addresses some of the issues and observations from data.

GENERIC SINUSOIDAL ENVIRONMENT
AT A SPECIFIC POWER LEVEL J

x1 - PUMP$_1$ SPEED, I.E. HPOTP
x2 - PUMP$_2$ SPEED, I.E. LPOTP

- SINUSOIDAL ENVIRONMENTS

  - PRIMARILY TURBOMACHINERY RELATED

    - FLOW NOISE FROM TURBINES & PUMPS
      - IMPELLERS, BLADES, DISCHARGES
      - $G \rightarrow f(\omega^2)$

    - UNBALANCED ROTATIONAL LOADS
      - ROTOR UNBALANCE & FORCES
      - $G \rightarrow f(\omega^2)$

    - OVERALL POWER LOSS
      - BARRETT APPROACH
      - $G^2 \rightarrow f$ (POWER, VIBRATION RESPONSE)

    - FREQUENCIES, F_{xi}, FUNCTION OF
      - PUMPS SPEED
      - SIGNIFICANT FLOW INTERRUPTIONS $\omega = x_i -$ PUMP SPEED

    - VIBRATION LEVELS, G_{xi}, FUNCTION OF
      - TRANSMISSIBILITY BETWEEN PUMP & LOCATION
      - LOAD VARIABLES

    - DEFINE Gx_i^2 & COV_{xi} BASED ON 26 LOAD DATABASE
      - OPB ACCEL FOR COMBUSTION
      - PBP ACCEL FOR PUMP LOADING

    - COMBUSTION OSCILLATIONS ANOTHER POTENTIAL SINUSOIDAL LOAD
      - LOW PROBABILITY — USUALLY ELIMINATED AS DESIGN GOAL
      - COMBUSTION INSTABILITY
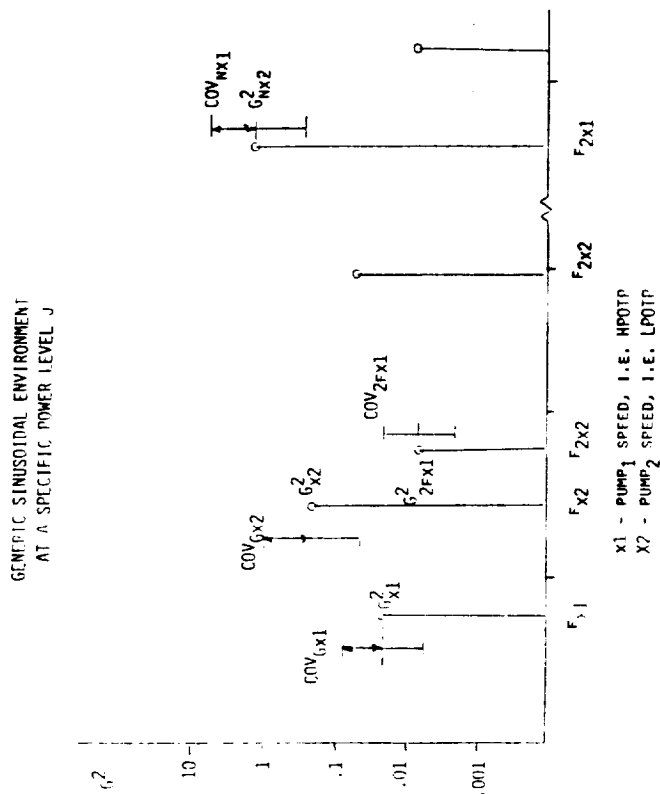
Figure 10. Generic Sinusoidal Environment

34

- CORRELATION PARAMETERS FOR G
  - ω^2 - ROTOR UNBALANCE & FLOW NOISE
    - $\sqrt{TQ \cdot \omega}$ - POWER FRACTION

- INFLUENCE COEFFICIENTS FOR NOMINAL CONDITIONS
  - $T = 4200T^2 + 5425T - 93$
  - $\omega = 2463T^2 + 16700T - 15400$

- NORMALIZED PARAMETERS (T^2 COEFFICIENT = 1)

  - $\dfrac{\omega^2}{3.45E8} = .017T^4 + .232T^3 + T^2 + 1.54T + .67$

  - $\dfrac{TQ \cdot \omega}{15E7} = .067T^4 + .56T^3 + T^2 + .533T - .01$

PARAMETER	T%	65	90	100	109	CORRELATION
ω^2		.61	.88	1.0	1.12	P. L. TO 1.3 EXP.
$\sqrt{TQ \cdot \omega}$		.66	.90	1.0	1.09	LINEAR WITH P.L.

ω - PUMP SPEED
T - THRUST, 1.0=> 100% POWER LEVEL (P.L.)

Figure 11. HPFTP Mechanical Vibration vs Power Level Correlation Parameters

- LEVEL OF X_I AND ITS MULTIPLES DEPENDENT ON CLOSENESS OF TURBOPUMP TO COMPONENT IN QUESTION

  - AT PRE BURNER

    - PUMP MODES STRONG FOR ADJACENT PUMP
      - HIGH TRANSMISSIBILITY
        - STIFF SHORT LOAD PATH
    - PUMP MODES LOW OR NON-EXISTENT FOR DISTANT PUMP
      - LOW TRANSMISSIBILITY
        - STIFF LONG LOAD PATH THRU P/H
        - FLEXIBLE LONG LOAD PATH THRU FLEX DUCTS TO LP PUMPS
    - COMBUSTION INSTABILITY DESIGNED OUT & DAMPED WITH DAMS AND ACOUSTIC ABSORBERS

  - AT MAIN INJECTOR

    - PUMP MODES LOW
      - MODERATE TRANSMISSIBILITY
        - STIFF LONG LOAD PATH
    - COMBUSTION INSTABILITY DESIGNED OUT AND DAMPED WITH DAMS AND ACOUSTIC ABSORBERS

Figure 12. Sinusoidal Environment

35

3.5 SSME Test History Experience and Potential Problems - Pops and Chugs

The one known significant problem on SSME associated with pops and chugs was an ASI line that ruptured during cutoff when the chug - a transient pressure oscillation - sucked hot gas and hydrogen into the ASI and ASI line. This resulted in a large magnitude detonation or pop. The pressure wave from the detonation ruptured the ASI line as noted in Figure 13. The fix was to change the shutdown purge operation.

There are significant variations in pops and chugs test-to-test and engine-to-engine. Duty cycle changes like cutoff level and purging are variables that affect pops and chugs. During a slow starting engine like the SSME, pops occur from both local gas pockets. Occasionally, there is a preburner pop into the high power regime (probably late LOX post ignition). After cutoff, the pops are the result of combustible gas pockets in the hot gas and preburner zones. No known pops have occurred in the main injector. The probability of a pop occurring is a function of the start and cutoff sequence and length of time during start. On a GG engine system like the J-2 that had a faster spin up start, local detonations are probably not separable from the basic transient loads. The potential for cutoff pops in the enclosed GG hot gas system, though, is there.

Pops are tracked on the SSME by time of occurrence and maximum peak-to-peak magnitude of the pulse. Chugs are tracked by frequency and magnitude. Even though there should be some inter-relation between pops and chugs, it is not apparent when the tracked parameters are over-plotted, e.g. see Figure 14. Reference 5 furnished background information on both pops and chugs from a general rocket engine standpoint.

Pops

The pop information has been tracked throughout the SSME engine program and has recently been translated into a computerized database. Separate files have been made for the individual preburners and main injector. The fuel preburner data is being used in developing a generic load model and the remaining data will be used for validation purposes.
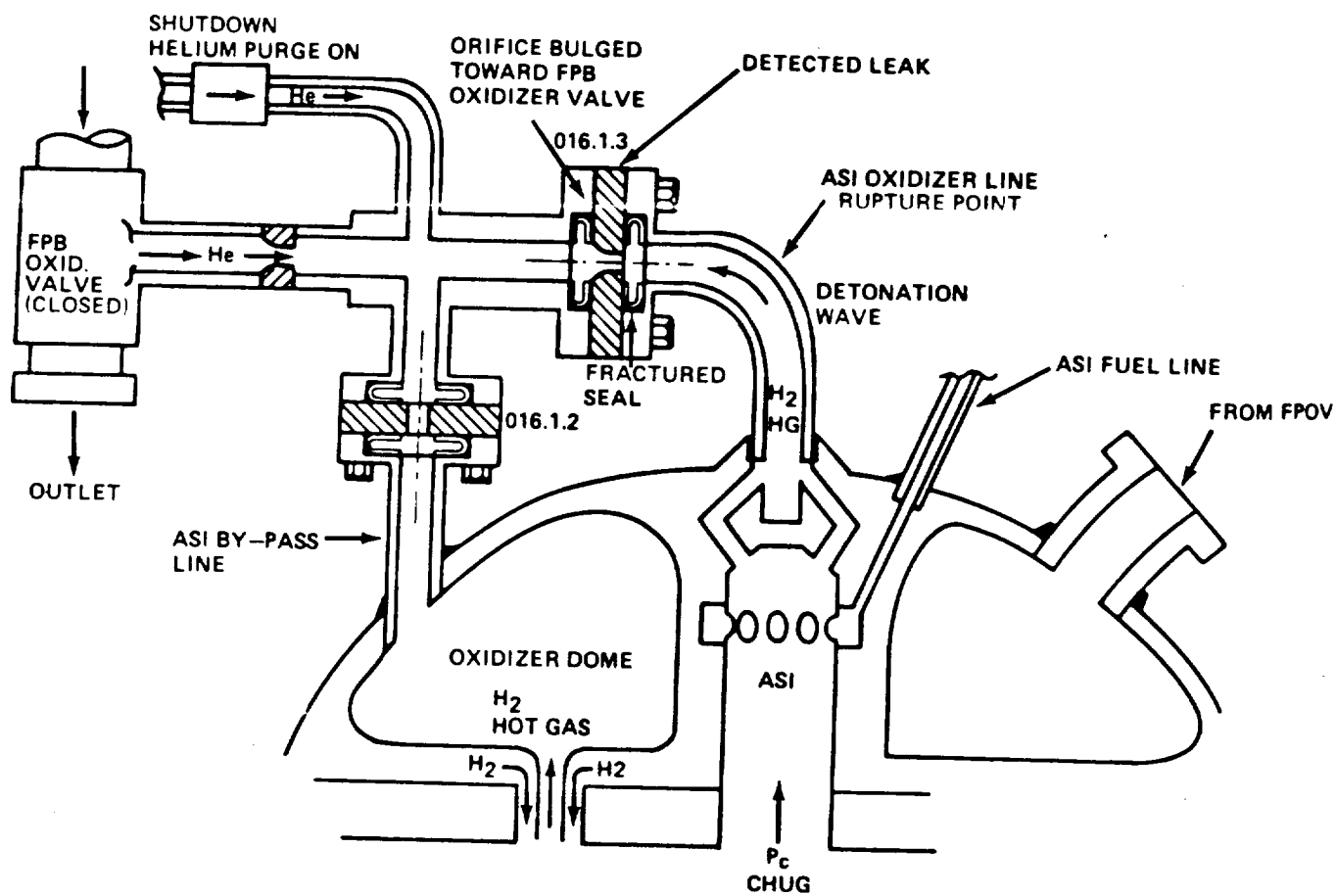
Figure 13. SSME Fuel Preburner
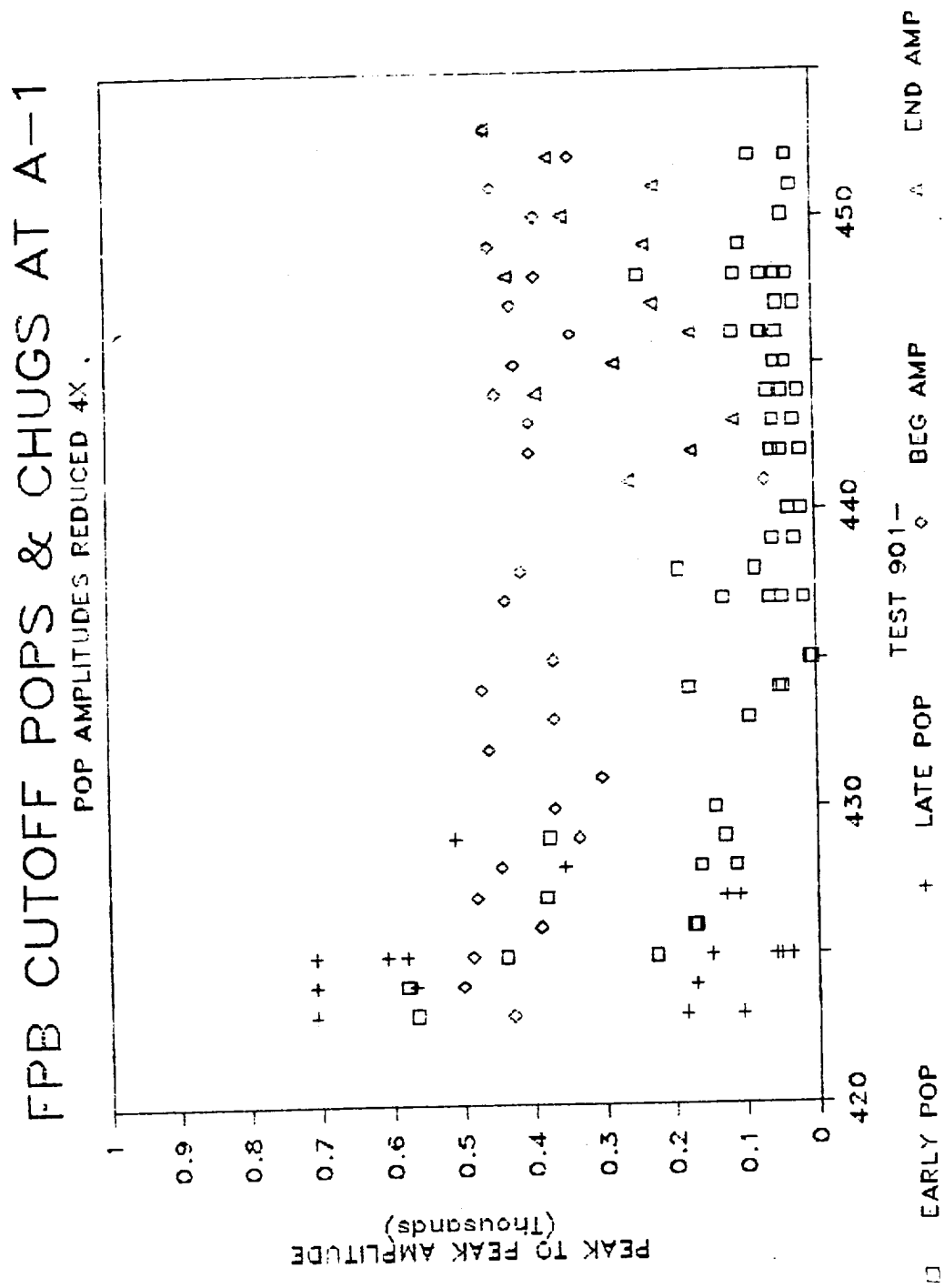
Figure 14. SSME FPB Cutoff Pops and Chugs at A-1

38

Figure 15 shows example plots of some of this information for the fuel preburner (FPB). The first plot relates the peak "pop" magnitude versus time and the second plot furnished the number of "pops" versus time. Little direct measurements such as high frequency pressure transducer data are available to correlate these vibration shock responses to actual engine variables, but expert opinion and technical reports will be developed for use in generalizing this data. As with many of the other variables on the engine, few comparable measurements are available from previous engines. The SSME has had much more extensive measurements than earlier production engines like the J-2 or F-1.

The pop and chug loads used in the development of a typical baseline set of information should be available in the expert systems to aid the user in his understanding of a specific load model. From a new user standpoint, one needs to have:

      1) information defining the load and its cause,

      2) how it is measured,

      3) how it is processed for use,

      4) whether a physical model is available,

      5) potential concern for damage,

      6) type of event,

      7) key variables,

      8) probabilistic model.

In addition, a baseline set(s) of mean values and coefficients of variations-COVs (or other parameters) are required.

Table 3 outlines a proposed format for furnishing this information to the user of the loads expert system. It covers the points listed above in a logical fashion. The baseline mean values and COVs for the load model will be added so that a user can judge whether they are adequate for his application.

Most of the information in Table 3 is self-explanatory except for the probabilistic model related items. In the probabilistic model, the engine-to-engine variation is considered an independent random variable

FPB POPS AT START

AMPLITUDE VS TIME

18 ENGINES   78 TESTS   92 POPS

NUMBER OF POPS VS TIME (50 MSEC STEPS)

18 ENGINES   78 TESTS   92 POPS
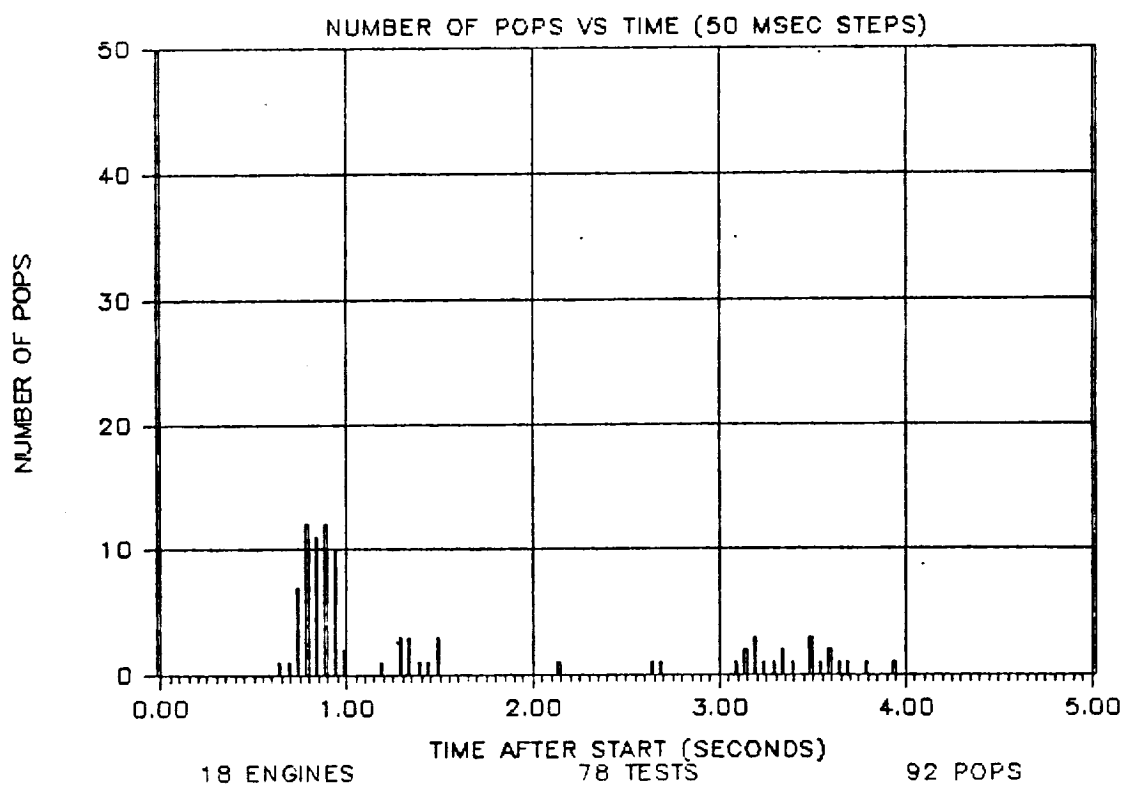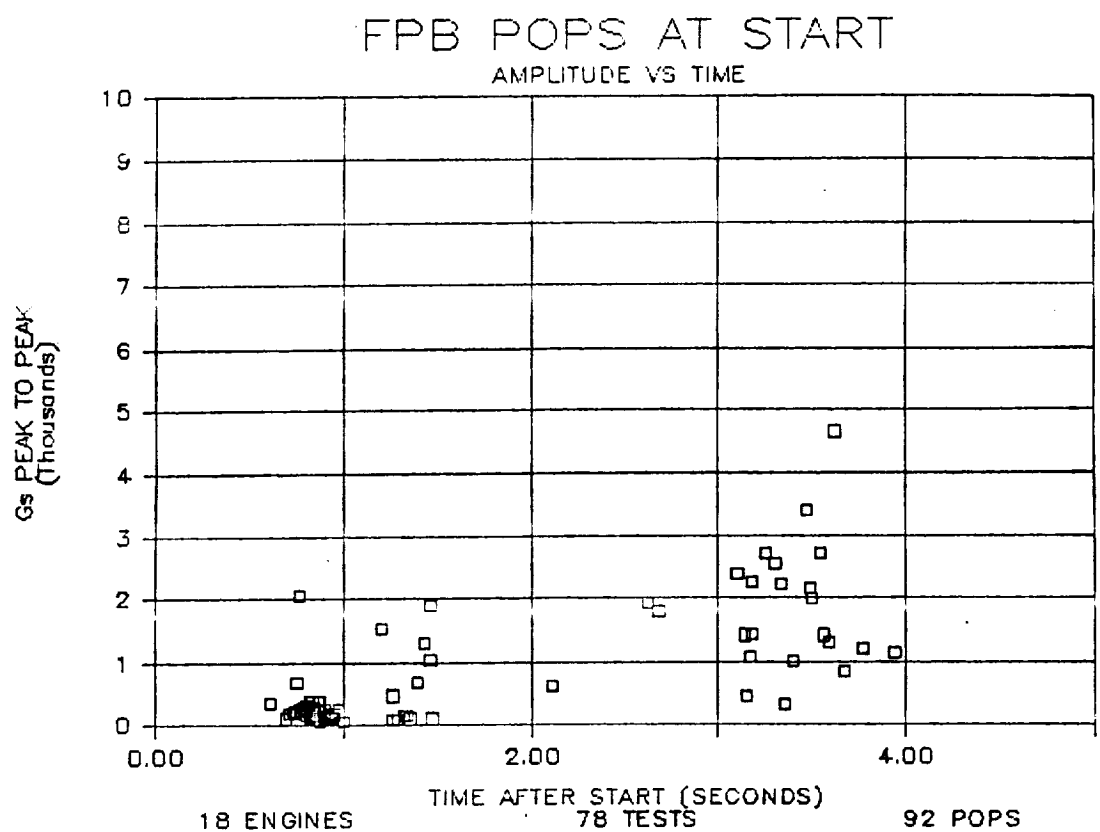
Figure 15.   FPB Pops at Start

40

Table 3
Pops and Chugs

1

1.1 POPS

1.11 DEFINITION	POP	A LOCAL DETONATION IN THE COMBUSTION ZONE REGION AND/OR ADJACENT HOT GAS SYSTEM. POPS OCCUR AT START AND CUTOFF. THE APPARENT CAUSE IS EITHER LATE INJECTOR ELEMENT IGNITION OR LOCAL POCKETS OF STATIFIED GAS THAT REACH A DETONATION CONDITON-APPROPIATE TEMPERATURE, PRESSURE AND MIXTURE RATIO. (STORABLES ALSO HAVE POPS AT MAINSTAGE-ASSOCIATED WITH INJECTING LIQUIDS AND MIXING)

1.12 HOW MEASURED

ACCELEROMETERS LOCATED ON LOCAL STRUCTURE. EXTERNAL TO INJECTOR.

1.13 HOW PROCESSED

PEAK MAGNITUDE AND TIME OF OCCURANCE WITHIN DEFINED TIME PERIODS. SHOCK RESPONSE OF REPRESENTATIVE DATA. STATOS RECORDS FOR QUALITATIVE LOOK.

1.14 PHYSICAL MODEL

TBD

1.15 POTENTIAL CONCERN FOR DAMAGE

START SYSTEM SMALL LINES
LOX POST/INJECTOR
TURBINE BLADES AND NOZZLES
SHEET METAL
INSTRUMENTATION PROBES

1.16 TYPE OF EVENT

COMMON IN GENERAL-SUFFICENT SHOCK LEVEL TO CAUSE DAMAGE TO SSME,RARE EVENT IN STEADY STATE OPERATION ON SSME

1.2 GLOBAL VARIABLES

ENGINE TYPE

STAGE COMBUSTION- MAIN INJECTOR,PREBURNERS AND DUCTING AND ASSOCIATED MIXTURE RATIO -SLOW START BOOTSTRAP ENGINE

GAS GENTERATOR- MAIN INJECTOR,GAS GENERATOR AND DUCTING

EXPANDER CYCLE- MAIN INJECTOR -SLOW START

1.3 G-VARIABLE

STAGE COMBUSTION

1.31 I-VAR

PREBURNER(PB)   MAIN INJECTOR(MI)

1.4 II-VAR

1.41 GENERAL

1.411 ENGINE TO ENGINE VARIATION	I	I
1.412 DUTY CYCLE CHANGES (START & C/O SHAPE & TIME, SS LEVEL)	DET	DET

1.42 START

Table 3 (Continued)
Pops and Chugs

	STAGE COMBUSTION	
	PREBURNER(PB)	MAIN INJECTOR(MI)
1.421 CHUG		
1.422 LOX POST IGNITION	IP	I
1.423 LOCAL GAS POCKETS	IP	
1.424 BLOWBACK-OPB	IP	
1.43 STEADY STATE		
1.431 LOX POST IGNITION	I	I
1.44 CUTOFF		
1.441 CHUG		
1.442 LOCAL POCKETS MIXED WITH HE	I	I
1.45 LATE POPS		
1.451 LOCAL GAS POCKETS	I	

1.5 PROBABILISTIC MODEL		
	START	FAC*ENG*DC*(BB+LP+GP)
	SS	FAC*ENG*DC*LP
	C/O	FAC*ENG*GP
	POST C/O	FAC*ENG*GP

1.6 DATABASE FORMAT OF LOADS	DISTRIBUTION OF MAXIMUM LOAD IN POP
	SPECTRUM SCALED TO MAXIMUM LEVEL OF POP

FAC-SCALE FACTOR
  1.411
  1.412
LP-LOX POST INGITION
GP-GAS POCKETS
I-INDEPENDENT SERIAL
IP-INDEPENDENT PARALLEL
DET-DETERMINISTIC

NOTE: BLOWBACK CAN OCCUR WHEN THE INJECTOR DOME CAVITY HAS SOME GAS IN IT
AND BACK PRESSURE PUSHES HOT GAS UP THE INJECTOR POST.
IN THE SSME THIS OCCURS IN THE OPB,BUT NOT THE FPB WHICH HAS ITS
DOME PRIMED TO A LIQUID STATE PRIOR TO THE BACKFLOW STATE.
J-2 HAD GG BLOWBACK INTO VALVE SEAT,START
SEQUENCE CHANGED TO ELIMINATE.

NOTE: THE PROBABILISTIC MODEL CONSIDERS THAT THE TIME PHASING WITHIN
THE SPLIT UP PORTION OF THE DUTY CYCLE IS NOT IMPORTANT TO THE COMPONENT
LOADS,E.G. THE DAMAGE POTENTIAL IS THE SAME THROUGHOUT THE START TRANSIENT.
THIS MAYBE CHANGED LATER.

that has a wide variation engine-to-engine. Start and cutoff duty cycle modifications are more of a deterministic parameter. Pops and chugs are different during start, steady state, and cutoff, so their probabilistic parameter estimates are also different. Preburners and main injectors also have differences, so they are also separated. Pops and chugs typically occur during transient conditions, but rarely occur during steady state operation.

Chug Loads. The chug load format has been prepared in keeping with the pop data approach for presenting data (see Table 4).

The text information is self-explanatory. In this case, a physical model can readily be developed for use in the options portion of this contract. Chugs occur each test during start and cutoff, and like pops are a form of combustion related instability. The probabilistic model is simpler than that proposed for pops since there is not the randomness of occurrence nor the multiple causative variables.

Internal Flow Dynamic Loads. Internal flow (i.e. inside ducts or components rather than external flow like shell flutter) has become critical environment on high energy flow systems like the SSME. A series of problems has occurred throughout the engine development that are related to fluid dynamics. The major problems have been reported elsewhere in the literature by Rocketdyne and NASA. A good summary of both vehicle and rocket engine related problems are summarized in Ref. 6. From Table 5 (reproduced from that document), it is readily observed that environmental problems on earlier engines were not a problem.

The only one noted was in J-2 (APOLLO) engine where engine propellant line bellows lack fluid structure coupled vibrations and failures. There are 8 listed for the SSME engine. These problems have spawned extensive analysis and testing within Rocketdyne and NASA to understand the associated phenomena and started toward developing better predictive environment methodology. All four components in this project have significant fluid dynamic loads.

43

Table 4

5.5

5.51 CHUG

5.52 DEFINITION CHUG

A CHUG IS A LOW FREQUENCY COMBUSTION INSTABILITY.
THE CHUGGING MODE FREQUENCY RANGE MAXIMUM IS SEVERAL HUNDRED HERTZ.
IN THIS FREQUENCY RANGE, THE WAVELENGTH IS MUCH LARGER THAN THE CHARACTERISTIC
DIMENSION OF EITHER THE CHAMBER OR FEED SYSTEM. THIS
RESULTS IN BULK FLUCTUATIONS OF PRESSURE WITHIN THE COMBUSTOR
AND ATTACHING MANIFOLDS.A CHUG INSTABILITY BEGINS WITH A LOW AMPLITUDE
SINUSIODAL WAVE SHAPE THAT GROWS IN A LINEAR FASHION TO A
HIGHER AMPLITUDE. THE INSTABILITY IS A RESONANT OSCILLATION IN ONE
OF THE FEED CIRCUITS COUPLED WITH A BULK OSCILLATION IN THE
CHAMBER. THE CHUG CAN BE A STEADY ATATE PHENOMENA OR A TRANSIENT
CONDITION.SINCE CHUGGING IS RELATIVELY WELL UNDERSTOOD, STEADY STATE CHUG
IS MUCH LESS LIKELY THAN TRANSIENT CHUGGING.

SSME
CHUG

THE SSME CHUG IS A TRANSIENT CONDITION AT START AND CUTOFF. IT IS ATTRIBUTED TO
EITHER A TWO PHASE-GAS AND LIQUID FLOW-IN THE LOX INLET MANIFOLDS AND/OR
A LOW DELTA PRESSURE ACROSS THE LOX POSTS.

5.53 HOW MEASURED

PRESSURE TRANSDUCERS LOCATED IN CHAMBER CAVITIES-PREBURNERS,
GAS GENERATORS OR MAIN CHAMBERS.

5.54 HOW PROCESSED

PEAK MAGNITUDE(S),OSCILLATION FREQUENCY AND START AND ENDING
TIME MEASURED FROM STATOS RECORDS. THE SSME TRANSIENTS MAYBE
ONE,TWO OR THREE PULSES OF DATA FOR EACH START AND CUTOFF.
EACH PULSE GROWS AND DIMINISHES IN MAGNITUDE AS THE ENGINE
OPERATION PASSES THROUGH THE CRITICAL REGION.

5.55 PHYSICAL MODEL

STANDARD METHODOLOGY FOR ANALYSIS AVAILABLE IN NASA SP-180

**5.56 POTENTIAL CONCERNS
FOR DAMAGE**

THIS FORM OF OSCILLATION MAY DO NO DAMAGE AT ALL.
STEADY STATE OSCILLATIONS HAVE RUPTURED FEED LINES AND JOINTS
FROM VIBRATION;ALSO A REDUCTION IN PERFORMANCE.
TRANSIENT CHUGS HAVE LESS AN EFFECT. SSME CHUGS OCCUR
FOR ABOUT 1 SECOND WITH HUNDREDS OF OSCILLATIONS OF VARYING
MAGNITUDES PER TRANSIENT.

5.57 TYPE OF EVENT

RARE FOR STEADY STATE CHUGS.
COMMON FOR TRANSIENT CHUGS.
SSME CHUGS OCCUR EACH TEST AT START AND CUTOFF.

5.6 GLOBAL VARIABLES

PROPELLANT FEED SYSTEM,INJECTOR DELTA PRESSURE,FLUID INERTANCE,
INJECTOR VOLUME,COMBUSTION TIME DELAY AND PROPELLANT PHASE(S).
A MIXTURE OF GAS AND LIQUID IN THE FEED SYSTEM READILY
INITIATE THE CHUG.

5.7 PROBABILISTIC VARIALBLES

5.71 ENGINE TO ENGINE VARIATION
5.72 DUTY CYCLE CHANGES
5.73 PULSE PARAMETERS-
   MAGNITUDE,DURATION,
   FREQUENCY AND
   NUMBER OF BLOSSOMS

I
DET

I

FAC-SCALE FACTOR
ENG-5.71
DC-5.72
NBLSM-NUMBER OF BLOSSOMS
TDUR-TIME DURATION
FREQ-OSCILLATION FREQUENCY
MAGN-PEAK MAGNITUDE OF BLOSSOM

5.8 PROBABILISTIC MODEL

START
SS
CUTOFF

FAC*ENG*DC*(NBLSM,TDUR,FREQ,MAGN)
"

X153

PROGRAM	AEROELASTICITY & INSTABILITIES	ENVIRONMENT	RESPONSE	MODELING	ACOUSTICAL TUNING	MODAL TUNING	MANUFACTURING/QUALITY
		FORCED RESPONSE					
APOLLO	1 WIND SOUNDING BALLOONS (UNISPHERE) 2 S-IVB SHELL MODE CONTROL FEEDBACK 3 S-IVB PANEL FLUTTER 4 1C OSCILLATING PLUME 5 1C POGO SA-1 6 II POGO SA-2 → 8 7 GROUND WINDS VORTEX SHEDDING 8 III STAGE OSCILLATING SHOCK 9 ENGINE PROPELLANT LINE BELLOWS 10 S-IV PROP UTIL GUIDANCE & CONTROL COUPLING	S-IVB ZERO G SLOSHING	WIND GUST LOAD RELIEF	1 INSTRUMENT UNIT II (U) LOCAL DEFLECTION 2 S-1C AND S-II PROPELLANT TANK HYDROELASTIC COUPLING 3 S-IVB SLOSH/INERTIA 4 S-IVB BAFFLE ORIENTATION 5 DYNAMIC TEST SUSPENSION SYSTEM COUPLING		SATURN IB INSTRUMENT TUNING	
SKYLAB	1 NON LINEAR APOLLO TELESCOPY MOUNT POINTING 2 1/2 HZ SYSTEM OSCILLATION	SOLAR WING LAUNCH FAIRING FAILURE	WIND GUST				
VIKING	1 VIKING SIMULATOR POGO 2 HELIOS POGO					VIKING SIMULATOR PAYLOAD (LONGITUDINAL) MODE TUNING	
JUPITER	SLOSH CONTROL COUPLING						
REDSTONE	1 RATE GYRO POTENTIOMETER FEEDBACK 2 OSCILLATING SHOCK						
SHUTTLE • SYSTEM	1 STOP SIGN FLUTTER (ON PAD FLUTTER)	1 SRB IGNITION OVERPRESSURE 2 LIFTOFF ACOUSTICS 3 ORBITER WING DISTRIBUTION 4 SSME HYDROGEN LEAD POP (OVERPRESSURE)	1 LIFT OFF LOADS SENSITIVITY 2 PAYLOAD LOADS SENSITIVITY 3 SRB HOLD DOWN BOLT LOAD 4 PERFORMANCE LOADS CONTROL COUPLING	1 SRB RATE GYRO COLD PLATE LOCAL DEFLECTION 2 SRB/ET ROLL MODE 3 SRB CASE ELONGATION		1 LIFTOFF LOADS SENSITIVITY 2 PAYLOAD LOADS SENSITIVITY	
• EXTERNAL TANK (ET)	AFT SKIRT THERMAL SHIELD FLUTTER	1 PROPELLANT INLET DIFFUSER CRACKING 2 PROTUBERANCE LOADS (CROSS FLOW)			PROPELLANT INLET DIFFUSER CRACKING	LOX TANK HYDROELASTIC DAMPING 2 UNSYMMETRICAL HYDROELASTIC COUPLING (LOX TANK)	
• SOLID ROCKET BOOSTER (SRB)		1 PARACHUTE & SWITCH EARLY CLOSING 2 PARACHUTE HANGUP 3 WATER COLLAPSE LOADS 4 WATER IMPACT SKIRT/ NOZZLE LOADS REVERSAL 5 IEA ISOLATION 6 NOZZLE EROSION 7 SKIRT WATER IMPACT TRANSIENT LOADS	1 PARACHUTE G-SWITCH EARLY CLOSING 2 PARACHUTE HANGUP 3 WATER IMPACT SKIRT/ NOZZLE LOADS REVERSAL 4 SKIRT WATER IMPACT TRANSIENT LOADS	1 VISCOELASTIC MODES 2 PRESSURE STIFFENING 3 FILAMENT WOUND CASE COMPOSITE CHARACTERISTICS	1 REENTRY ACOUSTICS (HIGH LEVELS) 2 INTERNAL MOTOR ACOUSTICAL TUNING		NOZZLE EROSION
• SPACE SHUTTLE MAIN ENGINE (SSME)	1 HIGH PRESSURE LOX AND FUEL PUMP SUBSYNCHRONOUS WHIRL 2 BEARING LIFETIME (PUMPS) 3 PROPELLANT LINE CONVO LUTES (VORTEX SHEDDING) 4 BI STABLE PROPELLANT PUMPS	1 STEERHORN FAILURE 2 LOX POST FATIGUE 3 MOV FATIGUE 4 LOX FLOWMETER CRACKS 5 ASI LINE FATIGUE 6 KAISER HAT/NUT FAILURE 7 CONTROLLER ISOLATION 8 TURBINE BLADE CRACKING 9 HEAT EXCHANGER COIL WEAR AND FAILURE	1 ASI ORIFICE 2 CAPACITOR PROBE FATIGUE FAILURE 3 PUMP UNBALANCE 4 BEARING LIFETIME 5 PUMP SEALS ETC RUBBING 6 MFV FATIGUE 7 IMPELLER FAILURE			1 MOV SEAL FATIGUE FAILURE 2 ASI ORIFICE FAILURE	1 WELD WIRE MIX UP 2 MOV SEAL FATIGUE FAILURE 3 PUMP UNBALANCE 4 PUMP SUBSYNCHRONOUS WHIRL 5 WELD OFFSET
SPACE TELESCOPE	1 LINE OF SIGHT JITTER 2 THERMAL CREAK		1 LINE OF SIGHT JITTER 2 SCIENTIFIC INSTRUMENT VIBRATION FAILURE	LINE OF SIGHT JITTER			
GRAVITY PROBE A	INTERNAL DAMPING/ INERTIA COUPLING						
HEAO	LAUNCH STAGE POGO	PAYLOAD THERMAL ISOLATOR	PAYLOAD THERMAL ISOLATOR	PAYLOAD THERMAL ISOLATOR			
IR			PERFORMANCE LOSS	LATCHES			LATCHES

Table 5

Dynamic Problems Experienced in Flight Vehicles

45

The HPOTPDD high pressure oxidizer turbopump discharge duct, the fourth component in the CLS study, is in the oxidizer pump discharge system where the flow environment is a key load, see Figure 16. High frequency pressure measurements such as those shown in Figure 17 are available. Also, considerable study is currently under way related to a problem in the injector LOX inlet area of the SSME. Table 6 lists the oxidizer system fluid flow problems as well as other hot gas system problems and Figure 18 shows three of the key variables that influence the loads in the oxidizer system. The power to weight ratio, pump pressures and dynamic velocity head have all doubled or tripled relative to other flight engines. The single variable that most effects the fluid-structural interaction in the hardware is probably the high value of the pump velocity head. In the SSME HPOTPDD, this parameter is much greater than on any other Rocketdyne turbopump or engine. Generic flow loads studies as part of the duct loads should aid in setting better limits of flow related parameters in new hardware designs.

Historically, conceptual or preliminary sizing of engine components are done scaling previous engine components using strength parameters, not environmental loadings like vibration or flow. The CLS effort should furnish additional criteria to make a more accurate sizing assessment starting from a conceptual design standpoint.

Similarly, the hot gas system has had a series of problems where the other three components under study are located. The initial fluid flow loading is being addressed in the hot gas system components to support the transfer duct and LOX post load modeling. Most of the SSME fluid environment flow modeling and measurements have been done in this system. The HPOTPDD load modeling will then be developed.

Figure 16. Location of HPOTP Discharge Duct
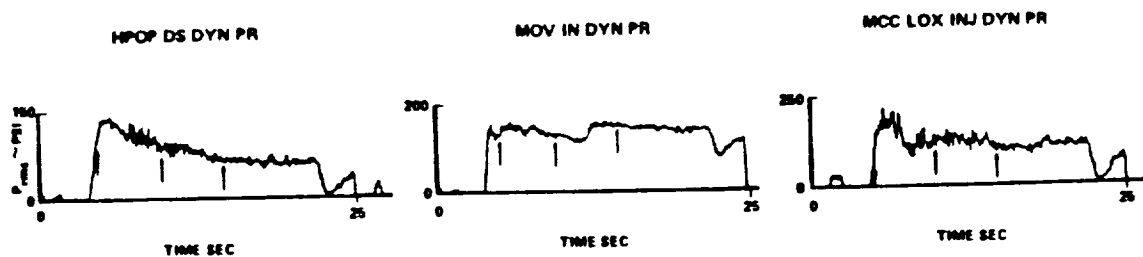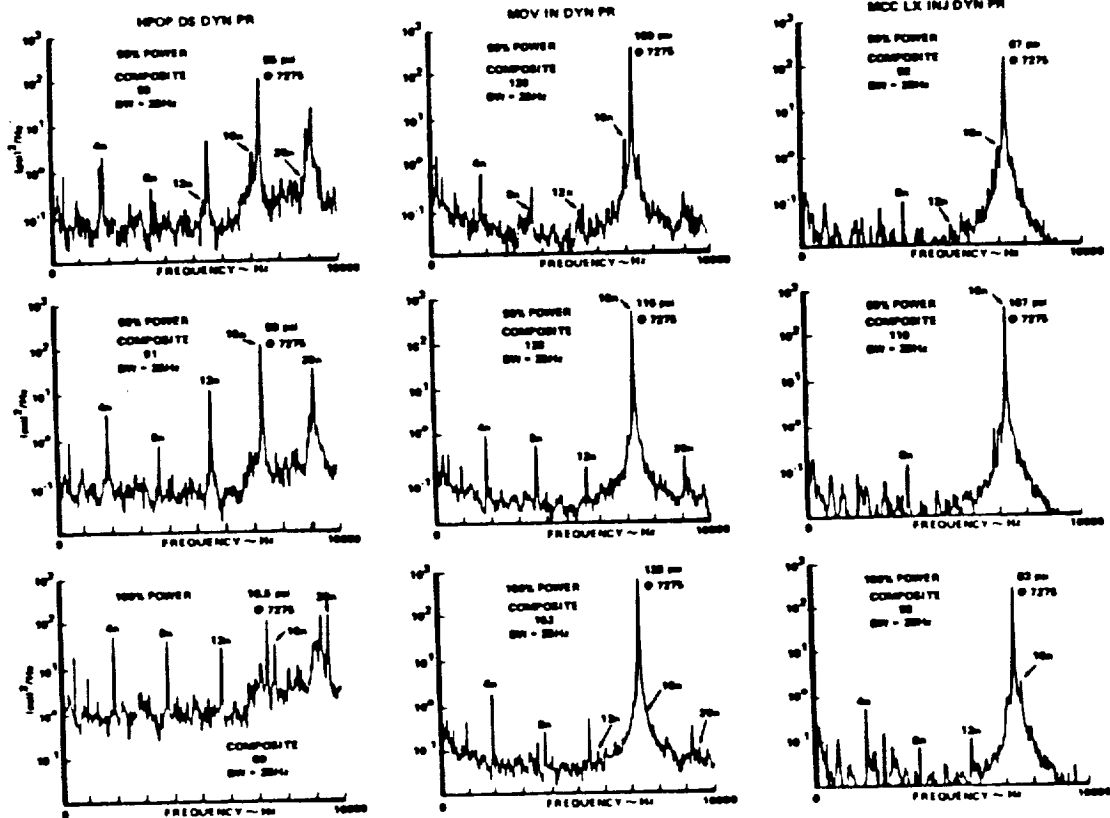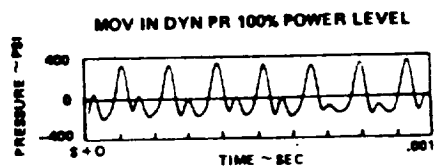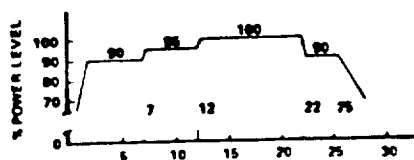
Figure 17. Typical Fluctuating Pressure Special Distribution (Test 013)

48

TABLE 6

SSME FLOW AND FLUID STRUCTURAL PROBLEMS

Problems in HPOTP Discharge System

- Flow Straightener (for Flowmeter)
- Flow Meter
- Oxidizer Valve
- HPOTPDD Lip Cracking
- Main Injector Inlet Vane - 4000 Hz

Problems in Hot Gas System

- Hot Gas Manifold Flow - Fuel Side
- Fuel Transfer Duct Coolant Liner - Fuel Side
- Preburner Lox Post - Fuel Side
- Main Injector Lox Post
- Bellows Shield - Fuel Side
- Turbine Blades
- Nozzle Steerhorn - Start Transient
- ASI Orifice - Cutoff Chug and Pop
- HPFTP Kaiser Hat/Nut Failure
- Temperature Probes

49
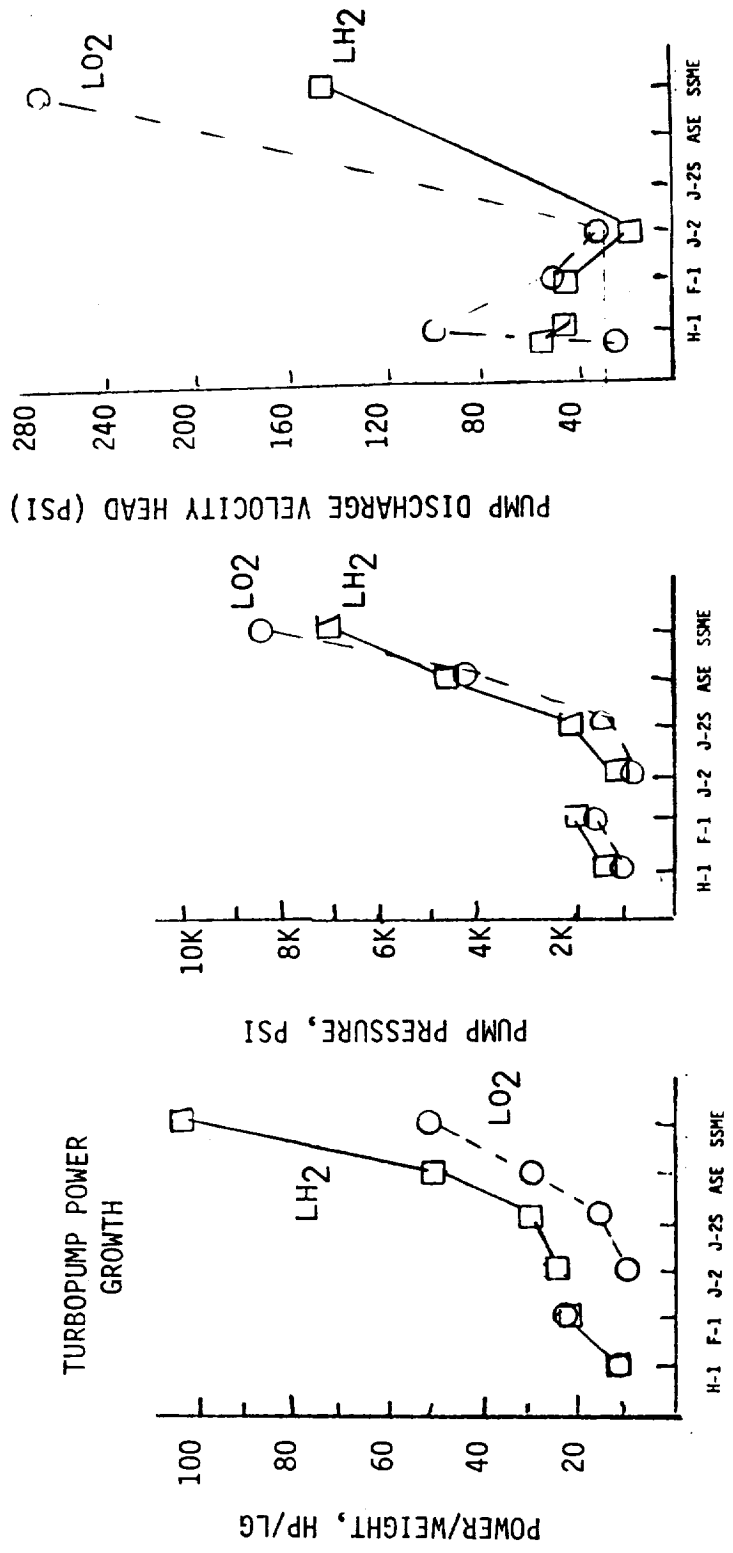
Figure 18. Key Factors for High Pressure Oxidizer System Flow Environment

4.0 TECHNICAL PROGRESS AND PROBABILISTIC MODEL DESCRIPTIONS

4.1 Introduction

The development of the probabilistic model for composite load descriptions during the second year has focused on the following topics:

(1) Data base development
(2) Transient load modeling
(3) Mission phase modeling
(4) Improvements to the probabilistic model
(5) Inclusion of expert opinion data
(6) Generic load calculations

The data base development has been progressing throughout the program. This is one of the essential developmental areas, since it is where the primary interaction between the probabilistic model and the expert system takes place.

The transient model was developed because the treatment of the loads during a transient event is fundamentally different from the treatment of the loads during the quasi-steady and steady state portions of the mission. In the transient model, the peak amplitude and the time of occurrence of this peak are treated as random variables. The nominal behavior is not separated from the load variation in this model.

Because there are up to 42 individual load and engine parameters which can influence the composite load calculation, it is important to provide a continuous, realistic transition between the three mission phase types. This linking of the mission phases has been accomplished, and compares well with available data.

An improved version of the primary probabilistic model, RASCAL, was incorporated into the computer code system. This version of the program allows the user to direct importance sampling schemes via input. Therefore, loads which are rarely occurring, but are potentially important for design or failure analysis, can be examined quickly.

51

Data from SSME designers and analysts on their expert opinion about the load variability was obtained and incorporated in the probabilistic model and data base. Additional information will be added as it becomes available.

Late in the year generic engine calculations were performed. These calculations will be improved and updated, as well as proceeding with the validation and verification, during the third year.

The following sections provide additional details about each of these areas.

5.0 PROBABILISTIC LOAD ANALYSIS FOR GENERIC SPACE PROPULSION ENGINES

5.1 Introduction

The development of a probabilistic load model for a generic space propulsion engine has been proceeding in several steps. At this time it is wise to reexamine these steps to illustrate how the program encompasses the goal of coupling the probabilistic load model, which predicts how mission and design changes will affect the critical loads in the specified engine, with the development of an expert system for load prediction.

5.2 Probabilistic Models For Generic Engines

To examine in detail how the probabilistic model will deal with generic engines, it is necessary to examine first the relationship between the probabilistic model and the expert system. Following this study, the developments in specific parts of the model during FY86 will be presented. Next, examples of the use of the model and the validation work to date will be presented. Appendix A furnishes details about using the code in a stand alone mode used during development. The probabilistic code ANLOAD (ANalyze LOADs) is being incorporated into the expert code by Rocketdyne.

An overall picture of the flow of information is provided in Figure 19. This is not meant to represent the current status of the expert system being developed by Rocketdyne, but rather is a representation of the information flow between the probabilistic model and the expert system. Some detailed discussion of this figure is warranted.

The critical information which must be communicated between the probabilistic model and the expert system is the mean, variance and distribution type for the individual loads and for the composite loads. As additional analyses are performed the database of information will be updated and previous analyses will be saved for future requests. Therefore, the important development work is in generating the new probabilistic information for individual and composite load parameters.

53
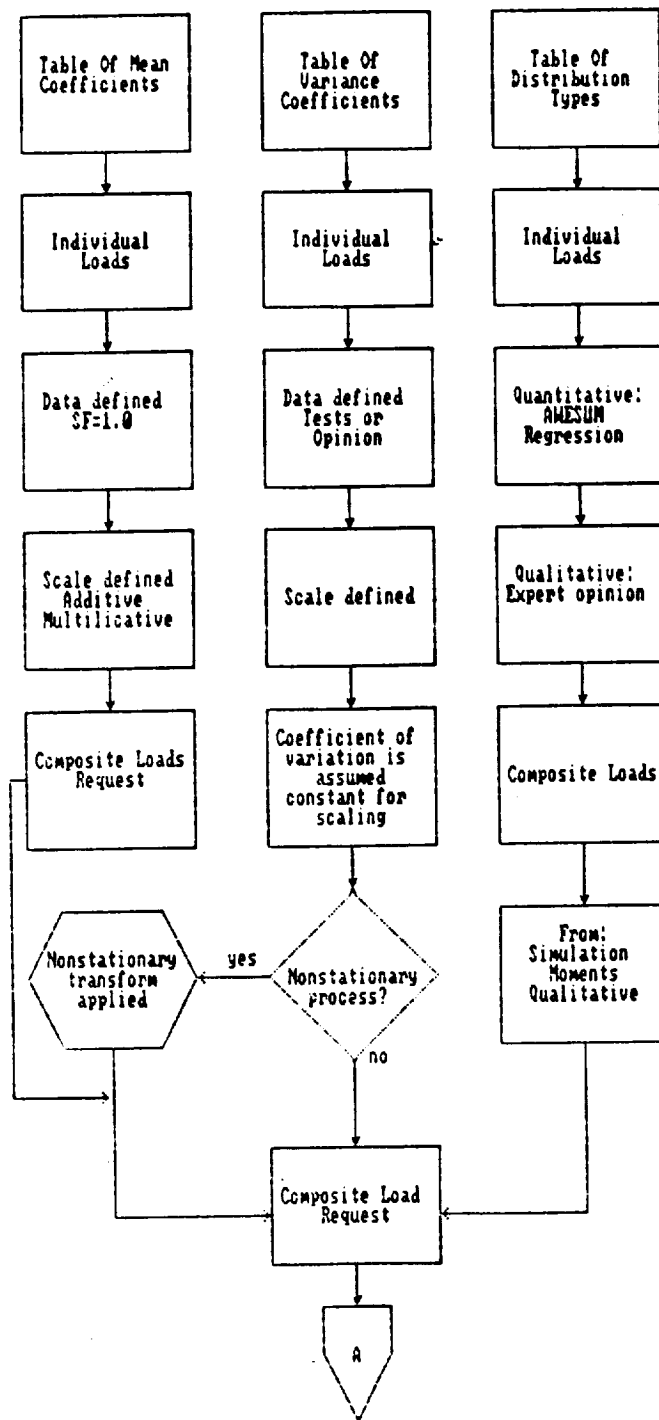
Figure 19. Interaction Between Probabilistic Information and Expert System
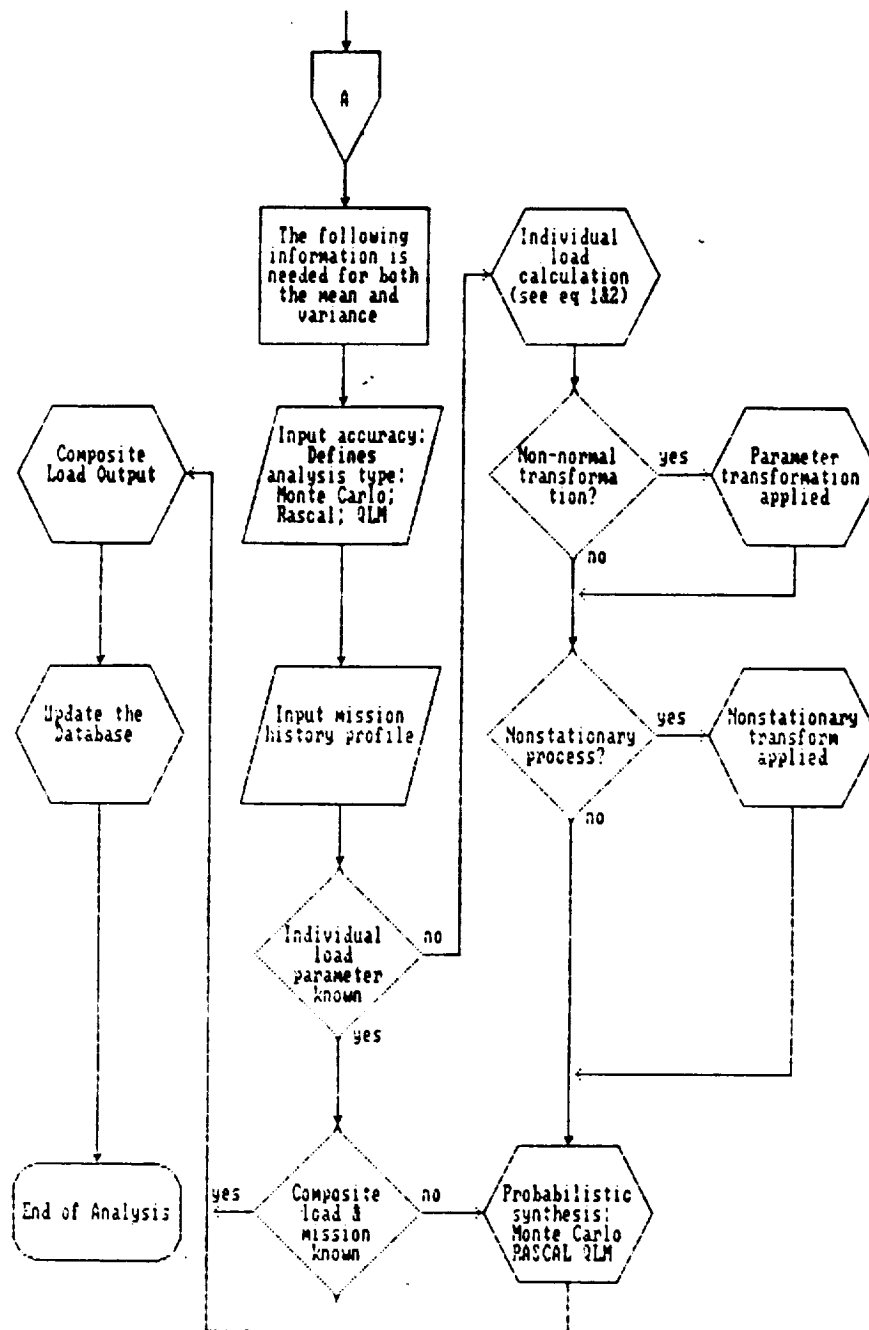
Figure 19. (Continued)

55

There are three boxes identified as tables; specifically, tables for the mean and variance coefficients, and the type of distribution which describes the data. In actual practice, these are not look-up type tables; rather they are function tables, e.g., those for the SSME influence functions. For each of these tables, the entries can be based on either previous data or analysis, or on scaling of data representative of one engine type to another. For example, the turbine speed in the J2 engine may not be known but, given the power requirements, it may be reasonably approximated by scaling known SSME data according to the power requirements. Thus, when individual parameters are unknown they are estimated by providing scale factors from better known, or understood, data bases.

These scale parameters must also be provided for both the mean and variance coefficients. One can envision a situation in which the mean value will scale based on one or more parameters, while the variance will be scaled based on a different set of parameters. For example, returning to the example of calculating J2 loads based on SSME loads, the turbine torque may scale according to the horsepower and speed ratios, but the variance will have to account for other differences in the engine. The reason is that the variance in the turbine torque is dependent on the other such variables. For example, head rise split between the two sequential pumps, the basic engine control philosophy, and the differences in a gas generator driven and a stage combustion cycle. Therefore, the table of variances must not only contain the total variance for the individual and composite loads, but it also must provide information on how this total variance is partitioned among the individual engine parameters and/or loads.

Once such tables have been defined, the expert system can then begin to quiz the user on the engine type and mission profile to be examined in the current analysis. This is identified as the Composite Load Request. The expert system then decides which are the critical loads for the problem to be analyzed and selects from the table the appropriate mean and variance coefficients, together with their associated scale factors. If a request for an analysis has been made in which all of the individual loads are known from previous analysis, then the scale factors are all set to one. If new

individual load data must be generated, the code selects that engine which is most closely aligned with the requested engine type. A specific turbine is also selected to reflect differences in the oxygen and fuel sides, and the appropriate scale factors are chosen.

Assuming that this is not a composite load analysis that has been performed previously, each of the individual loads to be included in the analysis are checked to insure that they are characterized probabilistically by their mean, variance and distribution type values. If the distribution type is non-normal, then the appropriate transformation is selected to calculate the distribution parameters based on the type of distribution which describes the individual load. Currently, it is assumed that the coefficient of variation for the individual load, as well as the composite load, is independent. If this is not the case, a quasi-steady analysis is called for in which the distribution parameters are allowed to vary in a time dependent fashion.

At this point all of the necessary probabilistic information has been collected and the probabilistic synthesis of the data can be performed. This synthesis is done using one of the three probabilistic models: (1) Monte Carlo, (2) RASCAL, or (3) QLM. The results are then sent to a post processor for display. Finally, the results of this analysis are placed in the data base for future reference.

5.3 Linking Different Mission History Phases

The insertion of a "probabilistic" model in the flowchart of Figure 1 is an over simplification of the actual process of interaction taking place between the expert system and the probabilistic analysis. In the actual analysis the expert system must be constantly updating the input to the probabilistic model so that the appropriate techniques, and data bases are used. One of the more difficult transition regions in which to perform this link occurs during engine start-up and subsequent power up to the demanded thrust levels. In this type of analysis three different mission requirements are demanded of the probabilistic model: (1) transient

analysis, (2) quasi-steady analysis, and (3) steady state analysis. However, each cannot be performed independently of the other since the loads are continuous functions. Thus, it would be inappropriate to have the transient analysis predict the (mean) temperature at the end of the transient phase to be $1000^\circ R$, while the subsequent quasi-steady state analysis is predicting a temperature at the start of the quasi-steady state analysis (i.e the end of the transient phase) to $2000^\circ R$. Thus, the transient analysis must be able to predict the load behavior during the defined time period, as well as provide a smooth transition to the subsequent mission phases. Similar arguments apply to the quasi-steady and steady state analysis. However, the difficulty in these situations is eased greatly when there are adequate functional relationships between the different phases, for example, as in the case for the influence functions for the SSME engine.

To illustrate the method for dealing with the transient response, an example using the SSME HPFTP temperature was examined. Figure 20 shows the analyses of three engine tests performed by Rocketdyne to calculate the turbine inlet temperature based on a combination of engine measurements and a turbopump model. Tests 902349 and 902363 show three distinct peaks (The third peak is much smaller in magnitude than the other two and occurs near 1.8 seconds.) in the temperature, while test 902356 appears to have only two peak values, at least relative to the other two tests. In addition, these peaks occur over a relatively narrow time period, on the order of tenths of seconds. The two questions to be addressed are: (1) how should the variable number of peaks be handled?, and (2) how should the variable magnitude of the peaks be handled?

Transient Temeperature Model
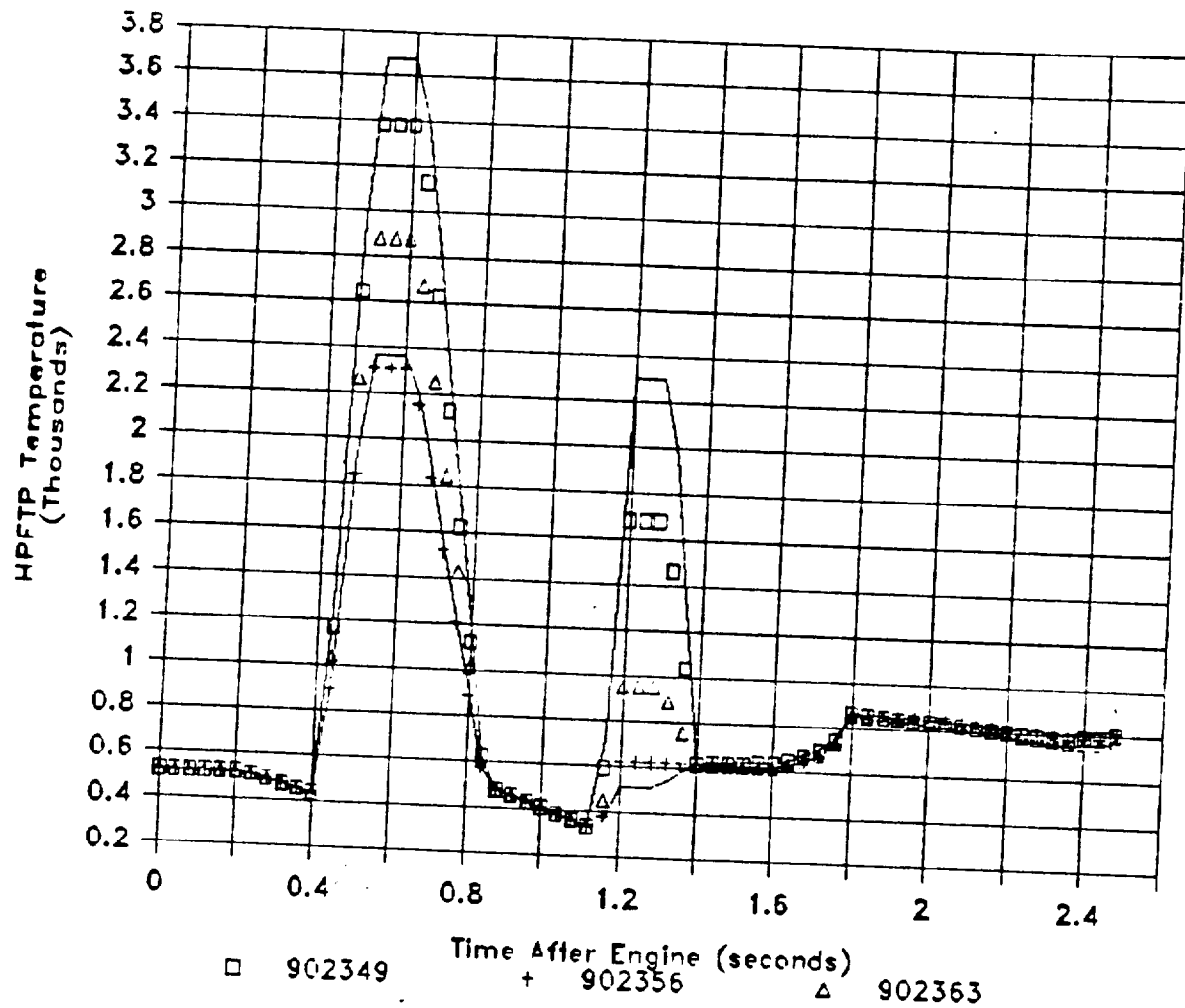
Figure 20   Selected Tests For the Temperature In the SSME HPFTP

5.4 Steady State

The input to the ANLOAD program requires that the beginning time and power level as well as the end time and power level be specified by the user. In some cases one or more of these parameters is forced by the program to ensure a continuous time line and power profile. During the quasi-steady and steady state phases of the time history, the influence coefficients are used to determine the loads seen at the critical components of the engine. During the transient phase, only the peak load value and the mean time of occurrence of this peak amplitude are of concern.

The testing of this transient model has been performed. There were several problems with the implementation of this method, the most significant one being the assignment of the variability of the independent engine parameters below the 65% power level. Because several of the parameters have non-physical predictions for their values below 65% power it is necessary to restrict the quasi-steady state phases to be applicable only above this power level.

5.5 Transient Load Model Development

The computer program PEAKS has been constructed to create a response envelope from the observed transient responses of the input variables to the influence functions. The response envelope defines the beginning, apex, and end of the individual transient events both in the magnitude and time domains. These critical points, the start, apex, and end, are hereafter referred to as knots. Due to the short duration of a transient response, random variation between consecutive knots is neglected, i.e. the response is assumed to be piecewise linear between knots.

PEAKS has the option for selecting various levels of accuracy when it constructs the response envelope. The first level of accuracy is provided by examining the first derivative of the response function to determine when the peak values occur. The calculation of the derivative can be made using the standard finite difference approximation, using central differences, or

can employ a four to twenty point moving average. This is done for the situation in which the data are oscillating about a mean trend line that is monotonic. In such a situation, the correct determination of the knots requires that these oscillations be smoothed to some extent so that true peak values can be observed. Example plots of these predictions are given in Figures 21 through 23.

PEAKS also has the ability to examine the second derivative (with the central difference finite difference approximation) to further refine the selection of the knot points.

The transient model for the example being considered is shown in Figure 23. In this figure the "+" symbols represent the average response of the data. The open boxes represent the mean transient model response. Finally, the solid lines are the bounds representing the two standard deviation spread about the mean value. As can readily be seen from Figure 21, if the lower bound is used, there will be only two peaks in the analysis.
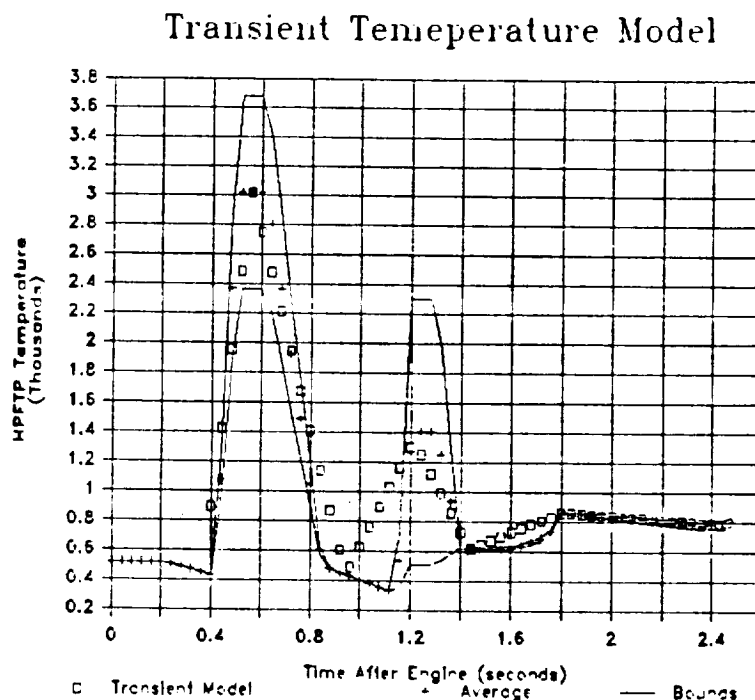
Figure 21   Probabilistic Model For Transient Analysis

The linking of the transient model with the quasi-steady state model should be checked at this point. For the SSME, the data analysis for temperature ends at approximately 5.0 seconds. From the data analysis, this appears to be at approximately the 86% power level. Averaging the available test data and calculating the standard deviation gives a mean and bounds for the temperature response. Then, this is compared with the calculations obtained from the influence function in order to calculate the temperature. These results are shown in Figure 22 where the break in the plot represents the break between the data analysis (less than 5 seconds) and the predictions using the influence functions (greater than 5 seconds).

Transient Temeperature Model
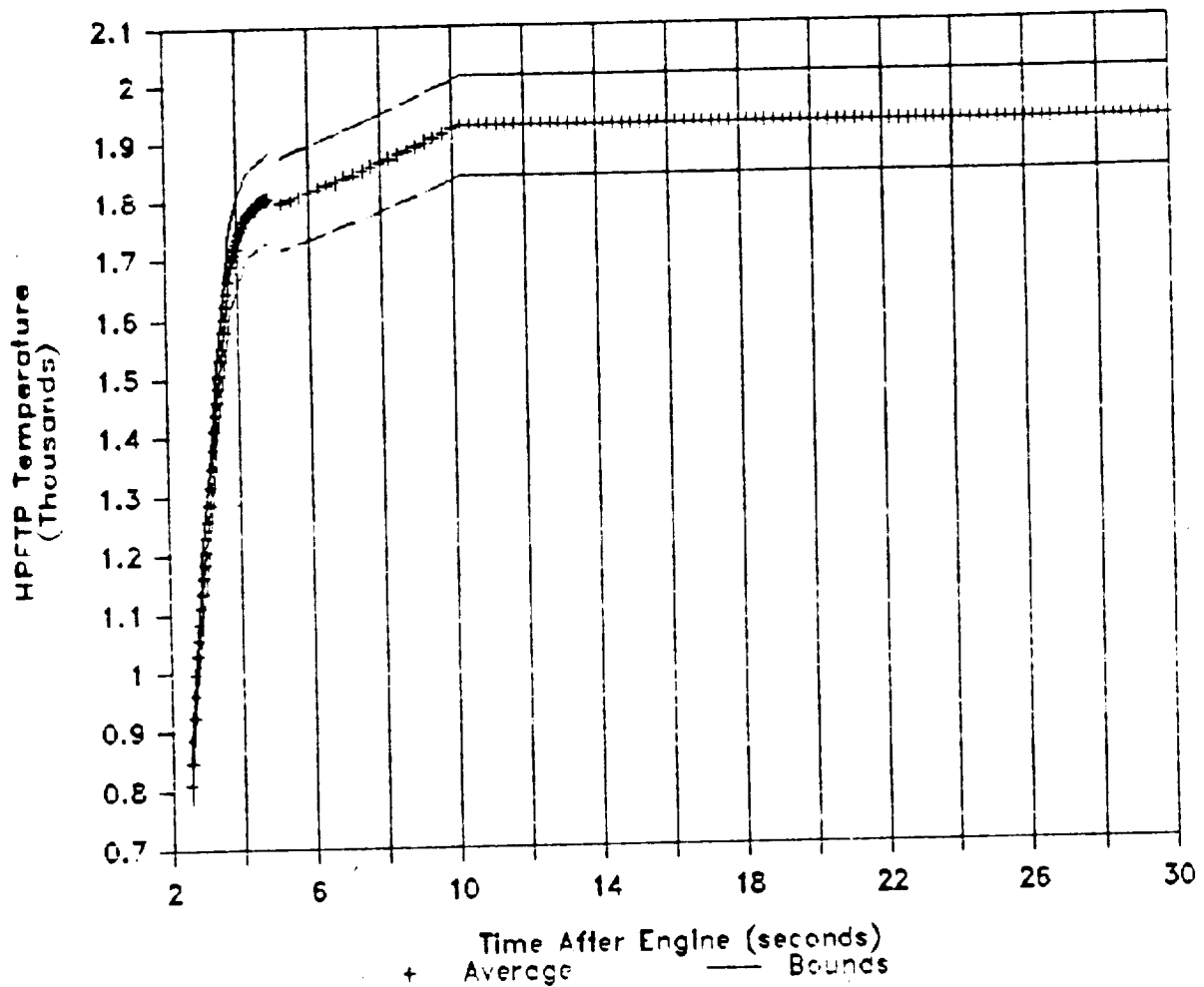
Figure 22   Transient And Quasi-steady Model Interaction

As this plot clearly shows, the link between the actual, observed data for temperature and the predictions between the temperature by the influence functions is quite good. To illustrate this point, Figure 23 shows the mean and bounds for the temperature if the transient data had simply been extrapolated from the 86% power level up to the full power level of 104%. The thick lines represent the results of the extrapolation. Clearly, the transient model is describing the temperature behavior well. Thus, the transient model described here provides the appropriate model for the transient and transition from transient to quasi-steady state analysis.

These models, and previous analyses with the steady state analysis, have shown that reasonable, cost effective, and accurate results can be obtained for space propulsion engines. However, because of the current information in the data base, almost all of the verification and validation of the computer codes have been performed for the SSME. There still must exist the capability to address, not only current engine, but also the model must be able to account for mission operations outside of the current experience as well as design changes. Clearly, radical departures from the existing engine types will be less accurately handled by the expert system, however, a capability for perturbations on the present state of knowledge should be manageable in the computer model.

5.6   Database Development

The development of a standard database for generic space propulsion engines is included in the computer code system. The current version of the code incorporates the data which have been derived from analysis of the independent load parameters. The program has been designed to provide the user with default values if none are provided during the interactive input session. Each time a default parameter is obtained from the data base it is identified, as well as the source of the data value from which it was obtained (e.g. SSME data analysis, expert opinion, etc.) Each of these default values, if selected, is automatically inserted into the input file being constructed by the user.

The database for generic space propulsion engines has been tested with a standard input problem to assess its use for a duty cycle calculation. A problem has been constructed which ramps up to 104% power level from 65%, remains at this steady state condition for several seconds, throttles down to 65% power level, operates at 65% for several seconds, and throttles back to 104% power. The current version of the code approximates the data which has been used in standard mission history profiles.

5.7 Using The Current Data Base

There are two situations to consider when developing a data base for use in a generic type of analysis. First, the analysis may ask for current engine designs, or mission requirements currently within the design specifications of a specific engine type. For example, one may wish to examine the effect of operating the SSME fuel turbopump at 106% power instead of 104% power. In these types of analyses, the deterministic analysis covers the range of
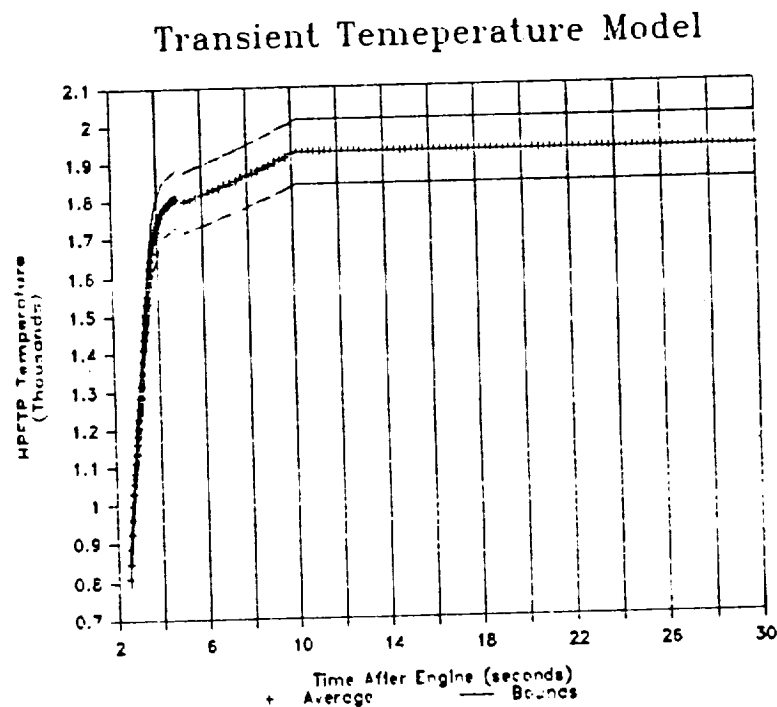
Figure 23 Extrapolation Of Transient Model To Full Power Level

64

physical parameters and the engine performance data and associated probabilistic information can be <u>interpolated</u> to predict the range of loads in the engine. Currently, the default for interpolation of the probabilistic data is to assume that the coefficient of variation (defined as the standard deviation divided by the mean) is constant and that the shape, i.e. distributional form, of the random behavior is constant. In this case the underlying deterministic model is used to obtain the new nominal level and the probabilistic parameters are readjusted to agree with the assumed value for the coefficient of variation. The probabilistic modeling then proceeds as described previously.

A more difficult use of the data base involves analyses for which no data for that specific engine or mission profile exists. Yet to be a truly generic analysis capability such situations must be addressed. In extrapolating the current experience with space propulsion engines to other mission requirements or design modifications it is necessary to make some assumptions about what will remain constant and what must be changed. The following hypotheses will form the foundation for the extrapolation process. These are default assumptions. If a user wishes to change one, or more, the capability will be provided.

<u>Hypothesis I.</u> The variable to be extrapolated will be described by the same distributional form describing the load variable in the current data base which is closest, in a physical modeling sense, to the variable to be extrapolated.

<u>Hypothesis II.</u> The variable to be extrapolated will be described by the a scaled value of the mean value for the load variable in the current data base which is closest, in a physical modeling sense, to the variable to be extrapolated. The mean value will be allowed to vary with the power level.

<u>Hypothesis III.</u> The variable to be extrapolated will be described by the same coefficient of variation (COV) for the load variable in the current data base which is closest, in a physical modeling sense, to the variable to be extrapolated. The COV will be allowed to vary with the power level.

Hypothesis IV. Non-normally distributed random variables will obtain a mean value from the appropriate scaling parameter under Hypothesis II and a variance from the COV under Hypothesis III. These parameters will then be transformed according to the distributional form given by Hypothesis I.

The manner in which these hypotheses are used will become clearer in the following section showing their use in an example. For now, an examination of the current data base and the behavior of the variance coefficients is discussed.

Mean Coefficients. The determination of the magnitude of the mean value of variables not in the data base will be handled primarily by the expert system. For example, if it is desired to predict the torque for an engine, a probabilistic model has no means for estimating what the nominal value should be if there are no data available for analysis. If the case under study is adding data to the data base, then the data analysis section of the probabilistic model will perform the appropriate calculations to estimate the mean value. Otherwise, it is assumed that the expert system provides the nominal levels for the necessary variables.

Variance Coefficients. While the mean levels of engine system related loads are primarily a deterministic quantity, the variability about the mean level is primarily a probabilistic quantity. However, unlike the mean, the expert system code may intercede to change the calculations described here based on data contained in its knowledge base. Thus, it must be remembered throughout this discussion that the rules applied here are generic in nature and may be modified as deemed necessary by the expert code.

There are two cases to consider in defining the variance coefficient table; (1) the individual load and/or engine parameter contribution to the overall variability in either the individual load or composite load being constructed, and, (2) the time dependent behavior of this variability. The first topic is important because of the differences which can exist between engine designs. For example, in the SSME significant variability exists in the high pressure inlet pressure. But since it is a two stage engine, such

66

variability is partially caused by the variability in the low-pressure outlet pressure. In a one-stage engine, one could imagine significantly less variability in the inlet pressure simply because there is no intermediate turbine. If a table is available which partitions the variability in the load variable of interest among all if the input parameters and loads in the calculation of this overall variability, the individual components can be "turned" on and off as demanded by the expert system. For the current data base, the engine system related loads are given by the influence functions:

$$L_p = \sum_{i=1}^{N} a_i \cdot L_i \tag{1}$$

$$L_i = \sum_{k=1}^{4} a_{i,k} \cdot PL^{k-1}$$

$$Var(L_p) = a_i^2 \; Var(L_i) \tag{2a}$$

$$(COV(L_i))^2 = \frac{Var(L_i)}{L_i^2} = \sum_{j=1}^{M} b_j \left[\sum_{k=1}^{4} (C_{j,i,k} \cdot PL^{k-1})^2 \cdot (COV^2(X_i)) \right] \tag{2b}$$

L_i = nominal engine value for dependent load

$a_{i,k}$ = nominal engine coefficients for calculating mean value of L_i at PL.

PL = power level

$C_{j,i,k}$ = Influence coefficient set

$COV(x_j)$ = Coeff. of variation of independent load j

$COV(L_i)$ = Coeff. of variation of dependent load L_i

b_j = On-off function for the independent variable j

Equation (5) provides a means for partitioning the variability in the load among the independent variables X_j and L_i, assuming that the independent variables are independent. This table has been constructed and is used in the examples discussed below.

<u>Time Dependent Behavior.</u> It is assumed that there is a one-to-one correspondence between time and the power level; therefore the subsequent discussion will talk of the COV as a function of the power level as opposed to time.

Figure 24 and 25 display plots of the COV for selected SSME variables as a function of power level. The symbols represent the calculated COV at one percent power level increments, while the solid line represents the best fit curve from a linear, exponential, logarithmic, and power curve functional forms. Each of the 20 turbine load variables was described with a curve similar to that shown in Table 7. In many cases the regression coefficient, r^2, was very close to 1.0 and, therefore, a very good fit was obtained. However, in some cases, a low value of r^2 was obtained. An example is the HPFTP torque in which r^2 is equal to 0.3253. The best fit line together with the influence function predictions are shown in Figure 26. Obviously, the fit is very poor. The important point to note is that the absolute magnitude of the COV changes only in the third decimal place over the entire applicable range of the influence functions. In this case, the expert system has the model assume that the COV is constant. Based on the data analysis, Table 8 presents the nominal levels for the COV as a function of the power level.

SSME HPOTP Inlet Temperature
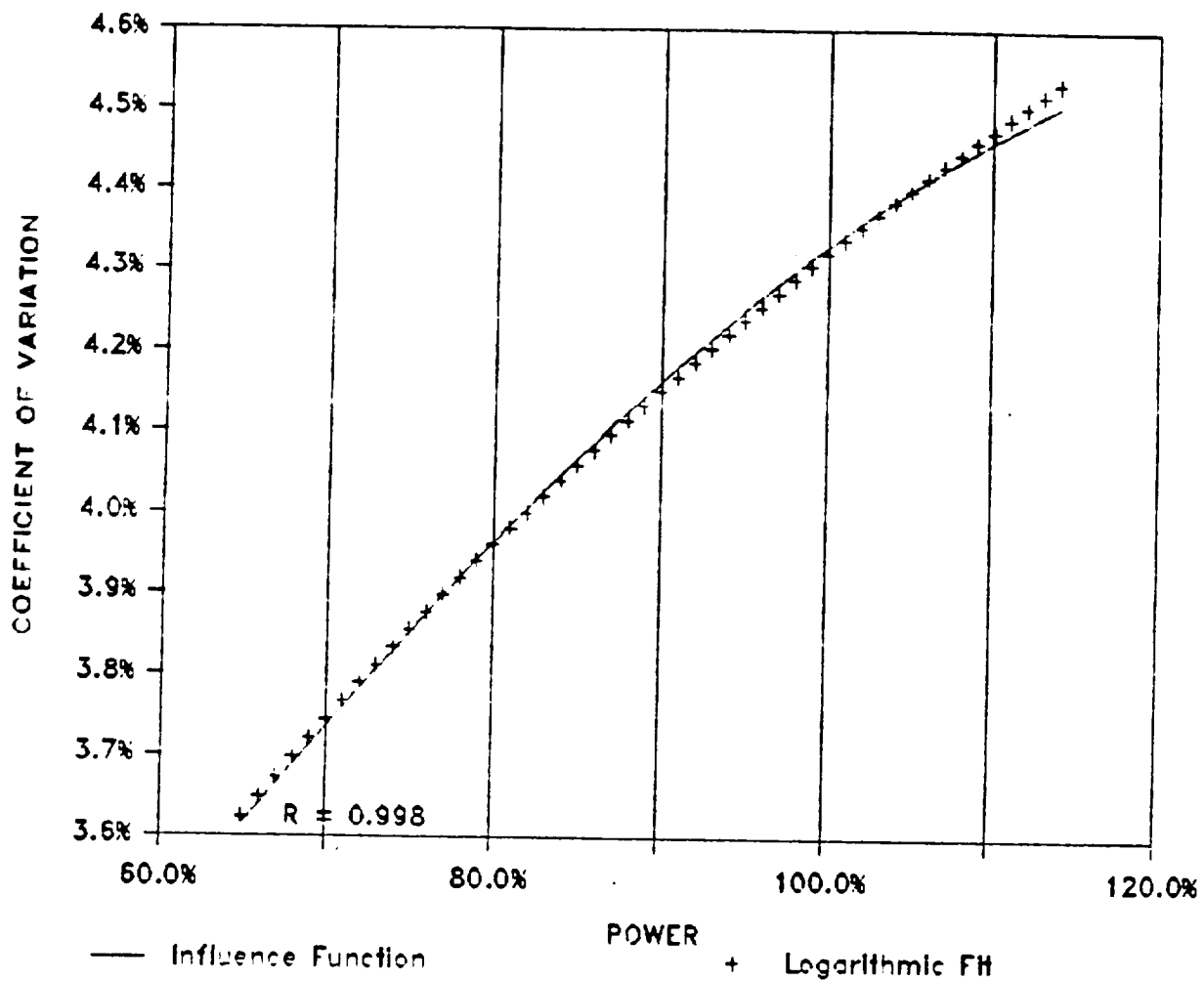
Figure 24. SSME HPOTP Inlet Temperature COV as a Function of Power Level

The amount of information and how it all fits together is best illustrated by way of examples. Therefore the following section discusses some calculations which have been constructed to illustrate the methods discussed previously.

69

SSME LPOTP Discharge Pressure
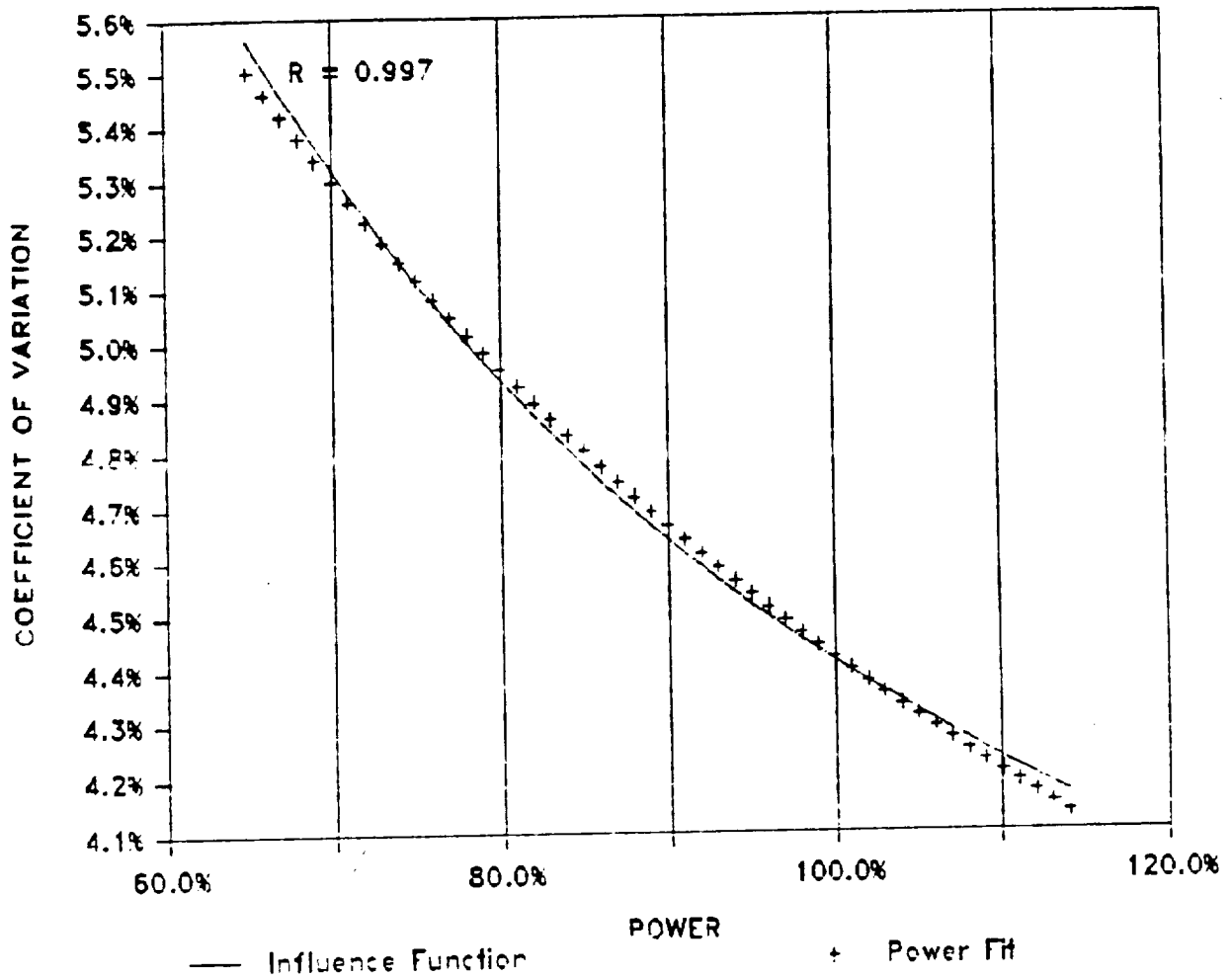
Figure 25. SSME LPOTP Discharge Pressure COV as a Function of Power Level

5.8 Improvements To The Probabilistic Modeling Code

The predictions currently being made by the ANLOAD program are based on simulation methods which are time consuming to produce. The primary reason is that low probability events are of interest in this program and the Monte Carlo method is slow for such predictions while the barrier crossing method

TABLE 7

COEFFICIENT OF VARIATION AS A FUNCTION OF POWER LEVEL

Variable: SSME	Curve Type	a	b	r^2
LPOTP Torque	Exponential	-5.212E-01	1.030E-02	9.999E-01
LPFTP Torque	Logarithmic	1.322E-03	1.250E-02	9.985E-01
HPOTP Torque	Power Curve	-4.362E-01	5.798E-03	9.646E-01
HPFTP Torque	Linear	2.450E-05	4.675E-03	3.253E-01
LPOTP Flowrate	Power Curve	-6.293E-01	3.170E-03	9.634E-01
LPFTP Flowrate	Power Curve	7.746E-03	9.409E-03	3.334E-02
HPOTP Flowrate	Logarithmic	2.435E-03	1.398E-02	9.941E-01
HPFTP Flowrate	Logarithmic	1.125E-03	1.187E-02	9.919E-01
LPOTP In Press	Power Curve	6.598E-01	3.844E-03	1.000E+00
LPFTP In Press	Exponential	8.889E-02	4.846E-03	8.084E-01
HPOTP In Press	Linear	3.366E-03	3.852E-03	9.995E-01
HPFTP In Press	Logarithmic	1.981E-03	6.537E-03	9.728E-01
LPOTP In Temp	Linear	2.295E-04	7.172E-03	9.964E-01
LPFTP In Temp	Linear	-1.318E-03	8.632E-03	8.080E-01
HPOTP In Temp	Logarithmic	1.618E-02	4.321E-02	9.986E-01
HPFTP In Temp	Exponential	-1.246E-01	2.701E-02	7.072E-01
LPOTP Out Press	Power Curve	-5.095E-01	4.419E-02	9.970E-01
LPFTP Out Press	Exponential	5.398E-01	9.023E-04	9.132E-01
HPOTP Out Press	Logarithmic	8.128E-04	1.863E-03	9.991E-01
HPFTP Out Press	Logarithmic	1.223E-03	3.285E-03	1.000E+00

Linear Curve: $\quad COV(P_L) = a \cdot P_L + b$

Exponential Curve: $\quad COV(P_L) = b \cdot e^{ax}, \ x = P_L$

Logarithmic Curve: $\quad COV(P_L) = b + a \cdot \ln(P_L)$

Power Curve: $\quad COV(P_L) = b \cdot P_L^a$

SSME HPFTP Torque
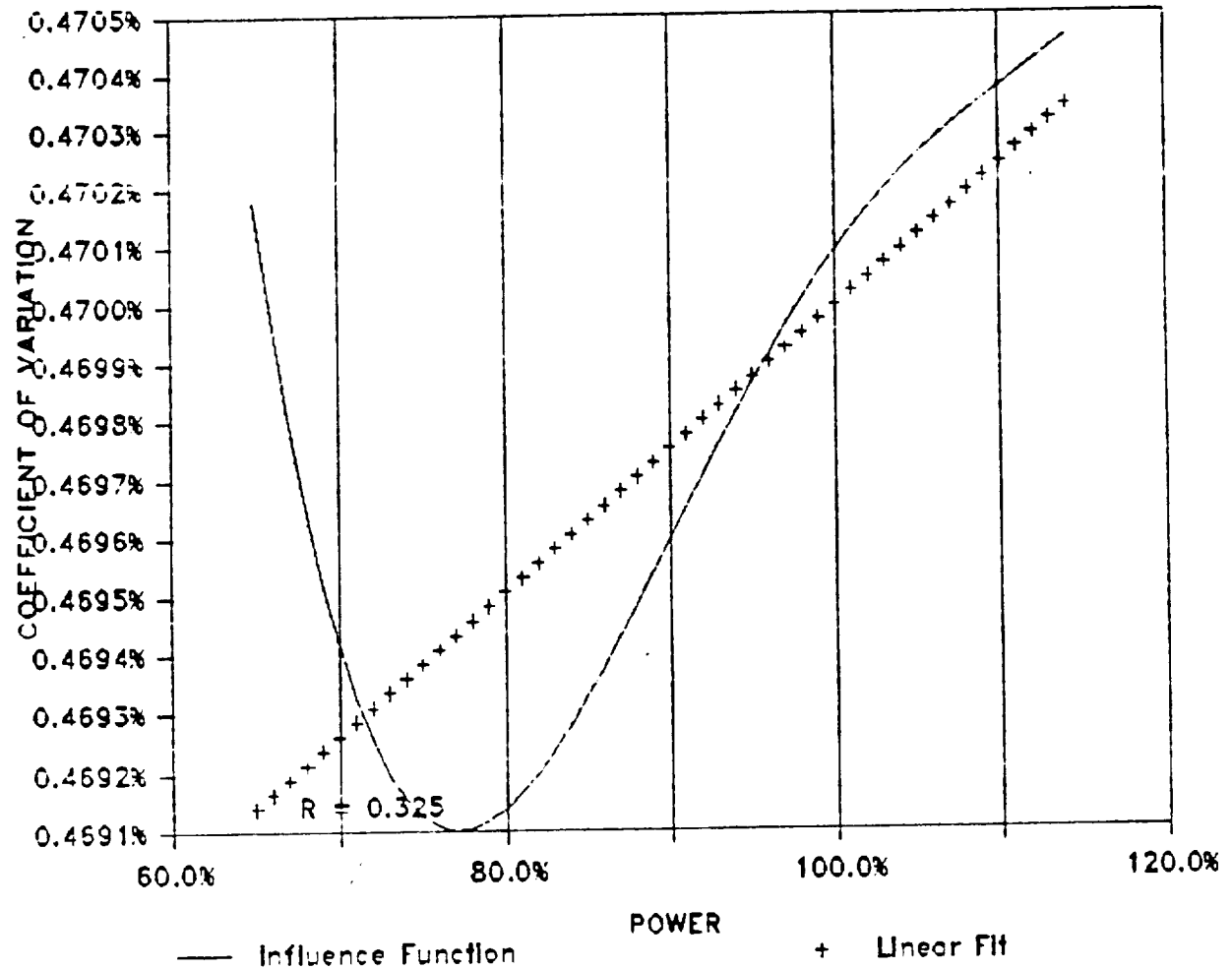
Figure 26   SSME HPFTP Torque COV as a Function of Power Level

TABLE 8
COEFFICIENT OF VARIATION AS A FUNCTION OF POWER LEVEL

Variable: SSME	Curve Type	a	b	r^2
LPOTP Torque	Exponential	-5.212E-01	1.030E-02	9.999E-01
LPFTP Torque	Logarithmic	1.322E-03	1.250E-02	9.985E-01
HPOTP Torque	Power Curve	-4.362E-01	5.798E-03	9.646E-01
HPFTP Torque	Constant		4.701E-03	
LPOTP Flowrate	Power Curve	-6.293E-01	3.170E-03	9.634E-01
LPFTP Flowrate	Constant		9.451E-03	
HPOTP Flowrate	Logarithmic	2.435E-03	1.398E-02	9.941E-01
HPFTP Flowrate	Constant		1.189E-02	
LPOTP In Press	Power Curve	6.598E-01	3.844E-03	1.000E+00
LPFTP In Press	Constant		5.281E-03	
HPOTP In Press	Linear	3.366E-03	3.852E-03	9.995E-01
HPFTP In Press	Constant		6.563E-03	
LPOTP In Temp	Constant		7.401E-03	
LPFTP In Temp	Constant		7.367E-03	
HPOTP In Temp	Logarithmic	1.618E-02	4.321E-02	9.986E-01
HPFTP In Temp	Constant		2.400E-02	
LPOTP Out Press	Power Curve	-5.095E-01	4.419E-02	9.970E-01
LPFTP Out Press	Constant		1.533E-03	
HPOTP Out Press	Constant		1.863E-03	
HPFTP Out Press	Constant		3.287E-03	

Linear Curve: $\quad COV(P_L) = a \cdot P_L + b$

Exponential Curve: $\quad COV(P_L) = b \cdot e^{ax}, \quad x = P_L$

Logarithmic Curve: $\quad COV(P_L) = b + a \cdot \ln(P_L)$

Power Curve: $\quad COV(P_L) = b \cdot PL$

73

and QLM technique, unless all of the inputs are normally distributed, are too approximate in nature to provide reasonable results. To examine the low probability events, either an importance sampling scheme for the Monte Carlo method or an improved version of RASCAL must be used. Of course a fourth probabilistic method could be employed. This has not been done for reasons which were given in the literature review completed earlier. The RASCAL method offers a variety of advantages for use in the expert system code – one of the primary ones being the ability to have the user define the range of the input probability density functions which he wishes to use. This capability allows the user to specify, by input, an importance sampling method. This capability has been included in the current version of ANLOAD and requires no new inputs, since the three parameters needed for input currently have been modified so that the third parameter specifies the lower limit of the input range to be examined. For example, if the following input is made for the fuel inlet total pressure:

ID	Mean	Standard Deviation	P_3
2	28.5545	7.38417	0.001

a normal distribution (ID = 2) with a mean value of approximately 28.6 and standard deviation of 7.4 is used to describe the random variation in the fuel inlet pressure. The value of P_3 set to 0.001 implies that the input probability density function will cover the range from the 0.1^{th} to 99.9^{th} percentile values. This is opposed to the equal probability version which would cover only the range from $100(1/N)^{th}$ to $100(1-1/N)^{th}$, where N is the number of bins used to describe the input variables DPD. In the sample runs constructed in the calculations shown in Figures 27 and 28 presented later in this section, N was set to 20; thus the possible range of input values is from the 5th to 95th percentile. As the figures show the variability of the results is changed significantly by limiting the range of the input distributions. It must also be noted that the values shown in these figures are for illustration only, since the physically realistic range of the input values was not limited for these calculations.

Additionally, a new random number generator was incorporated into the probabilistic code which should increase the period of the pseudo-random number generator by more than an order of magnitude (to approximately 17,000,000).

5.9 Quick Look Model

In some analysis only an approximation to the variability of the load is needed. In such a case the relatively long running time of the RASCAL or Monte Carlo simulation models is not justified. To provide a program which quickly calculates such an approximation the Quick Look Model (QLM) was developed.

The basic assumption made in the QLM model is that all of the individual loads and engine parameters used to predict the individual and composite loads are normally distributed. In this case the influence function tables can be used directly to calculate the mean and variance of the output. If there are dependencies among the variables then some modification to the current program is needed. However, if the correlation coefficient is provided, or calculated, then exact solutions are still available. The basic formulas used to perform these calculations are given by the algebra of normal distributions presented below. In these formulas μ represents the mean, or expected value of the random variable, and σ is the standard deviation, i.e. the square root of the variance.

These formulas are used in conjunction with the influence equations to provide the mean and variance estimates of the load variables. Since the influence functions currently in the probabilistic load model do not involve any divisions all of the formulations are exact (assuming independence), if the probability density functions are all gaussian.

75

Statistics Of The Sum: Z = X + Y

$$E[z] = \mu_x + \mu_y$$
$$V[z] = \sigma_x^2 + \sigma_y^2 + 2\rho\sigma_x\sigma_y \tag{3}$$

Statistics Of The Difference: Z = X − Y

$$E[z] = \mu_x - \mu_y$$
$$V[z] = \sigma_x^2 + \sigma_y^2 - 2\rho\sigma_x\sigma_y \tag{4}$$

Statistics Of The Product: Z = X x Y

$$E[z] = \mu_x \times \mu_y + \rho\sigma_x\sigma_y$$
$$V[z] = \mu_x^2\sigma_y^2 + \mu_y^2\sigma_x^2 + \sigma_x^2\sigma_y^2 \, 2\rho\mu_x\mu_y\sigma_x\sigma_y + \rho^2\sigma_x^2\sigma_y^2 \tag{5}$$

Statistics Of The Quotient: Z = Y / X

$$E[z] \approx \frac{\mu_y}{\mu_x}\left[1 + \frac{\sigma_x}{\sigma_x}\left(\frac{\sigma_x}{\sigma_x} - \rho\frac{\sigma_y}{\sigma_y}\right)\left(1 + 3\frac{\sigma_x^2}{\sigma_x^2} + \cdots + \right)\right] \tag{6}$$

$$V[z] \approx \frac{\mu_y^2}{\mu_x}\left[\frac{\sigma_x^2}{\mu_x^2} + \frac{\sigma_y^2}{\mu_y^2} - 2\rho\frac{\sigma_x\sigma_y}{\mu_x\mu_y} + 8\frac{\sigma_x^4}{\mu_x^4}\right]$$

Two options exist in the computer code for using the QLM model. If the user requests that the QLM model be used and all of the input distributions are not normal, then the corresponding mean and variance are calculated by the appropriate moment transformation. On the other hand, if the user does not request the QLM model, yet all of the input distributions are gaussian, then the QLM model is substituted. The QLM substitution is made since there is no reason to run a simulation to approximate an answer which can be obtained exactly with the QLM model. Figure 27 and 28 show comparisons of the QLM model to theory and the simulation methods.

5.10 Examination Of Model Suitability For Low Probability Calculations

The use of the probabilistic load model for the prediction of low probability events, such as pops (small, localized explosions in the engine), raised the question: are the available probabilistic methods the most suitable for addressing these types of calculations? To answer this question a study was performed which examined the use of a fast probability integrator, specifically the Chen-Lind (C-L) algorithm, as programmed by Wirsching and Wu[7] and the RASCAL program.

The C-L algorithm is an extension of the technique originally proposed by Rackwitz and Fiessler, Ref. 8. In this methodology, the Hasofer-Lind safety index is the value of the response variable that minimizes the distance from the failure surface to the origin in normal probability space, and the slopes of the probability density function are equal. The probability of failure is approximated as the value of the normal cumulative distribution function at the Hasofer-Lind safety index.

The comparison of the C-L and RASCAL algorithms was made using the sample problem in Ref. 7. The problem is posed as the determination of the probability of failure of a cylindrical pressure vessel having an external torque. Failure occurs when the Von Mises stress exceeds the yield strength.

77
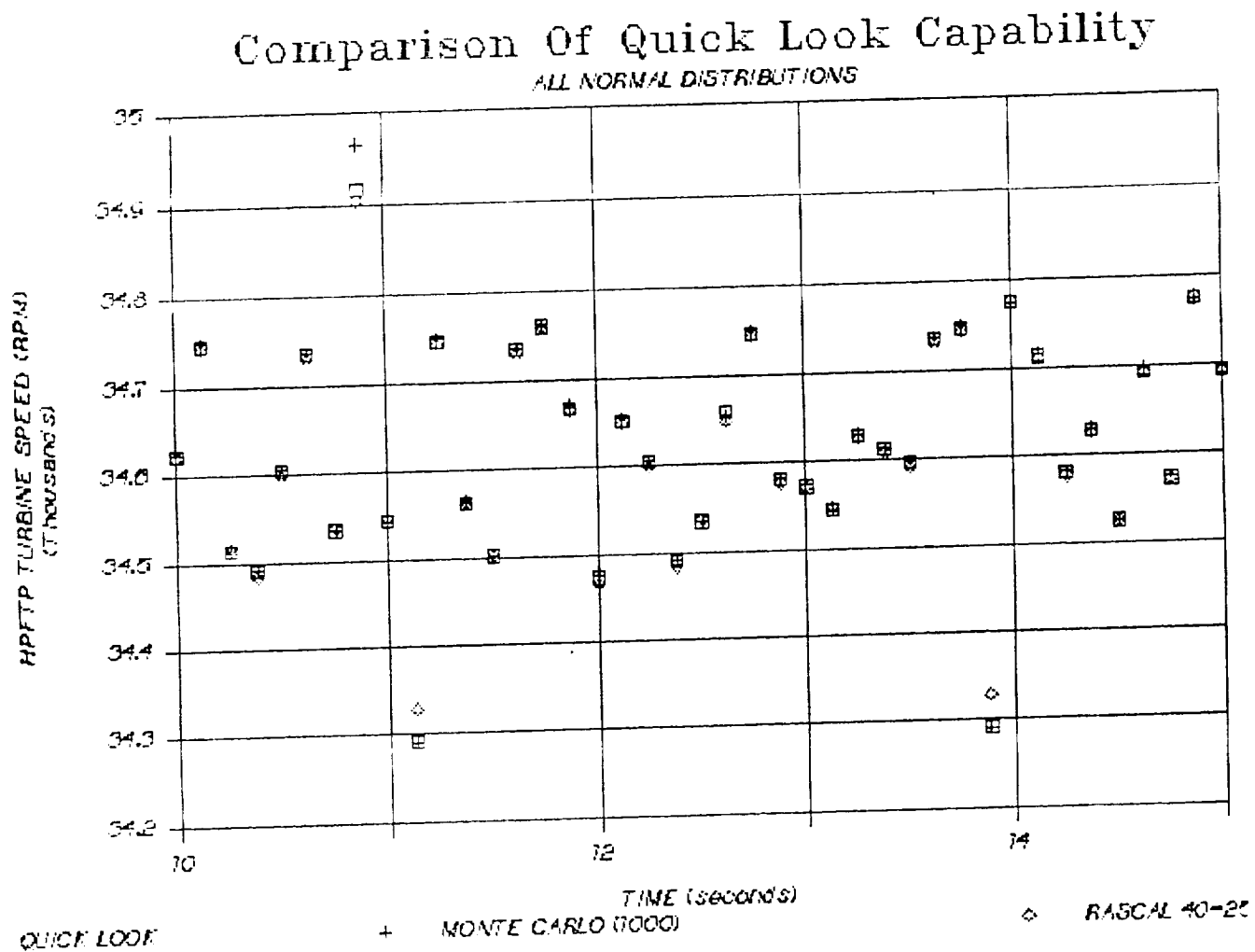
Figure 27. Comparison Of QLM Model And Theory
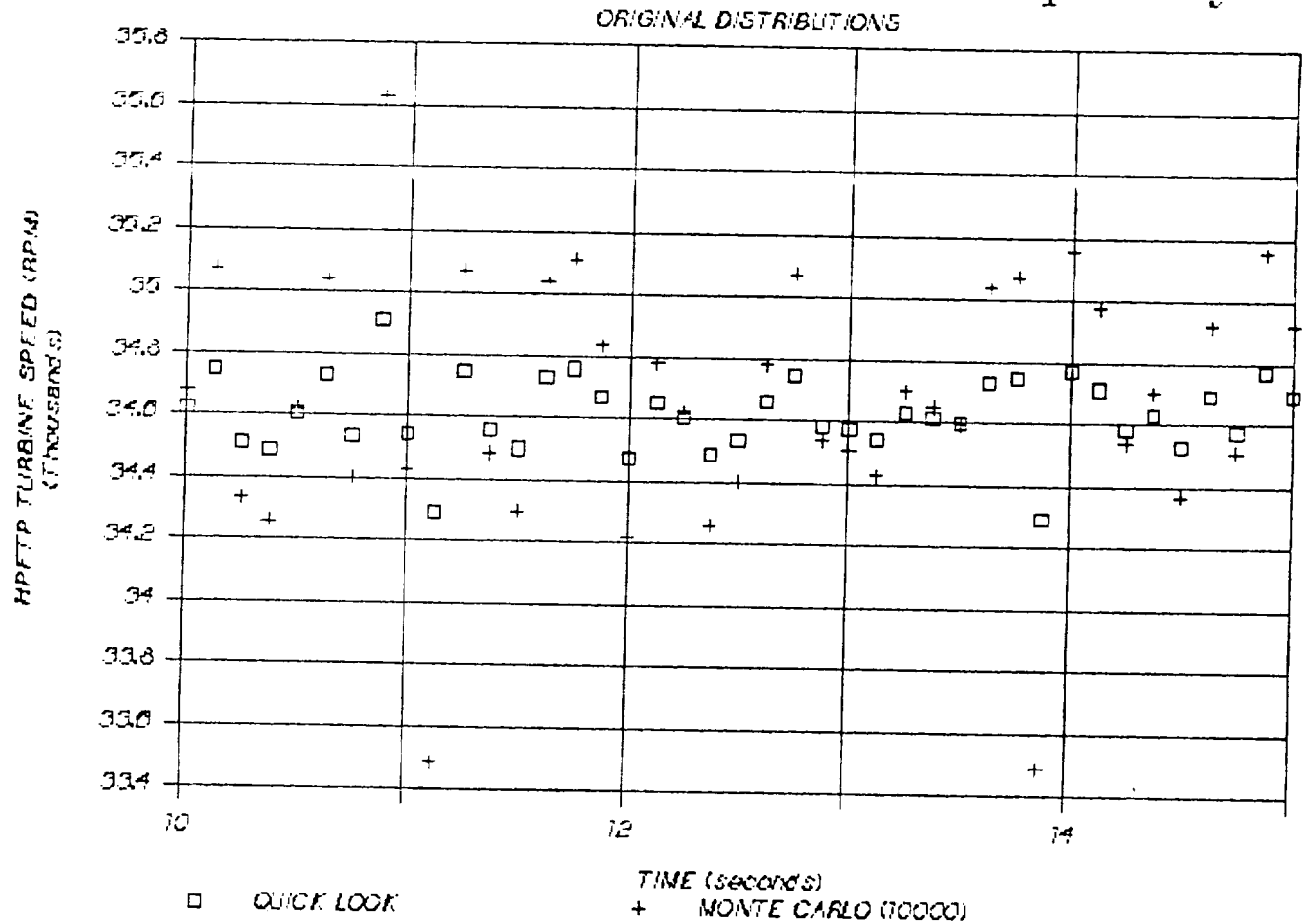
Figure 28.   Comparison Of QLM Model And Simulation Studies

79

Thus, the failure function is defined as:

$$G(\widetilde{u}) = R - (300*P^2 + 1.92*T^2)^{0.5} \qquad (7)$$

where

$\widetilde{u}$: Vector of random variables

P : Pressure

T : External torque

R : Yield strength

Each of the random variables is defined by the parameters in Table III. The vessel failure occurs when the value of G(u) is less than zero.

The results of the RASCAL calculations are given in Table IV, and compared to the results presented in Ref. 7. As this Table clearly shows, the RASCAL method provides the same level of accuracy for the failure probability calculation as does the C-L algorithm. In fact, the method is relatively insensitive to the RASCAL parametric values. There are several other important features of the calculations to be pointed out that indicate that the use of the RASCAL method is more appropriate for the low probability event calculations than is the C-L algorithm. The first of these is shown in Figure 29, where a plot of several of the RASCAL calculations is made versus the C-L calculation. The portion of the CDF shown in this figure shows the RASCAL calculations as single points for each individual run. Thus, for the RASCAL 250-40 where 250 is the number of intervals, and 250 times 40 (10,000) is the number of samples used, run each point denoted by an X represents the results of a single run of the RASCAL code. The straight line representing the C-L calculation is an interpolation (linear) between individual runs of the C-L program. This is necessary because the C-L algorithm provides only point estimates for the failure probabilities; it does not provide the entire CDF range, as is done in the RASCAL algorithm. To obtain the CDF of the failure probability it was necessary to run the C-L program 33 times. Of course this can be easily automated, however, it would still require a user to specify the levels at which the probability calculation be performed.

TABLE 9
RANDOM VARIABLE DESCRIPTIONS

VARIABLE	DISTRIBUTION TYPE	MEAN	STANDARD DEVIATION
R	WEIBULL	48.0	3.0
P	LOGNORMAL	0.9874*	0.16*
T	EXTREME VALUE I	20.0	2.0

*Median and coefficient of variation

TABLE 10
COMPARISON OF FAILURE PROBABILITY CALCULATIONS

METHOD	PROBABILITY OF FAILURE
MONTE CARLO	1.600×10^{-3}
CHEN-LIND	1.820×10^{-3}
RASCAL 10-50	1.945×10^{-3}
RASCAL 25-40	1.819×10^{-3}
RASCAL 20-400	1.823×10^{-3}

At the end of the run, it may be discovered that a significant portion of the probability curve was not covered, i.e. a portion of the CDF is missing. Again, this will lead to rerunning the program.

In contrast the RASCAL method automatically takes care of covering the widest possible range of the CDF in the available computational time. For the RASCAL calculation in which the input variables were divided into twenty discrete intervals, estimates of the CDF from the 10^{-9} level of probability up to the 99.9999th percentile value is covered automatically by this algorithm. This range is covered only if the variables are independent.

This study indicates that the RASCAL algorithm is the most effective probabilistic technique to use for generic space propulsion applications.

RASCAL Prediction: Failure Probability

Exceedance Of Yield Strength
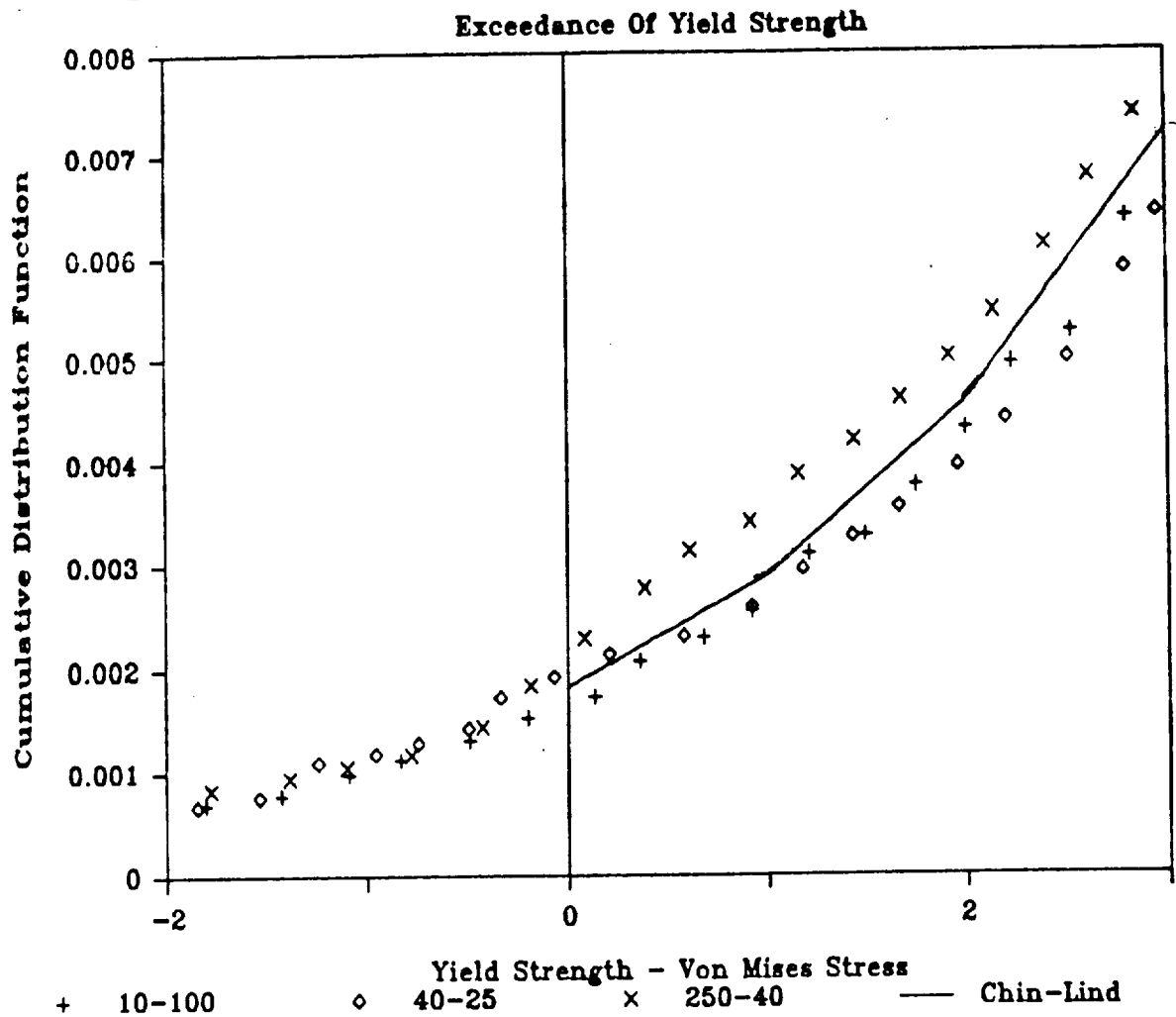
Figure 29. Rascal Versus Chen-Lind Failure Probability Predictions

5.11 Comparison of ANLOAD Predictions With Expert Opinion.

In the calculation of the engine loads during steady state operation, or when the loads are slowly varying, the probabilistic model contained in the ANLOAD computer program uses a set of engine influence coefficients that defines nominal operating conditions and effects of perturbations about the nominal point. The perturbations have been developed as a set of 33 independent variables that are used to account for engine-to-engine and test-to-test variations on the SSME engine.

As previously discussed, these variations were developed from consultations with the individual experts on specific hardware and covers geometric, performance, etc., conditions that can affect the engine operation. The purpose of developing these variations is to predict operating ranges for engine performance parameters such as pressures, temperatures, and flows. These random variations are added to the predicted performance effects of direct independent variation allowed by engine contract specifications to determine parameter minimum and maximum expected values. The direct independent variations include: propellant inlet temperatures and pressures, line resistance changes due to gimbaling, and tank repressurization flow settings. These maxima and minima define the operational limits used for engine component design and are used in developing the SSME engine balance.

These types of engine variability estimates are the type of information required for generic load definition in the CLS code. The variability estimates combined with the engine test results furnish an ideal set of information for verification of this portion of the ANLOAD code. Only 23 of the 41 independent variables are used for the influence coefficient load calculation in ANLOAD. This limitation is not strict since a new set of influence coefficients, if supplied, could include up to 42 independent variables. This is only the method which is currently used for the ANLOAD program. Thus, the SSME balance calculate variations should be somewhat larger than those calculated with ANLOAD. Also, the engine balance variations are based on maximum operation limits, whereas the ANLOAD variability is based on actual engine test variability. This implies that

the engine balance calculations are more conservative than the ANLOAD calculations since they account for the design operating limits, while the ANLOAD results are only taking into account the variability actually seen during tests or standard operations.

The first step in making the probabilistic predictions was to enter the expert opinion predictions of the variability in the independent parameters into the data base. These are reproduced in Table V. The coefficient of variation reported in Table V is the percentage value of the standard deviation of the nominal value at a specified power level (104%), assuming parameter in the engine, and should provide a reasonable test of the model.

The variation listed in Table 11 is in addition to the variability induced by the random nature of the processes, e.g. engine to engine variation. Therefore, when the probabilistic function is constructed, it will have this variability as an additional parameter in the functional relationship. With the assumption that all of the independent parameters which control the

TABLE 11
COEFFICIENT OF VARIATION FROM EXPERT OPINION
FOR SSME INDEPENDENT VARIABLES

Variable	Coefficient of Variation
Commanded Mixture Ratio	0.5%
HPFTP Turbine Efficiency Multiplier	1.0%
HPFTP Turbine Flow Multiplier	1.0%
HPOTP Turbine Efficiency Multiplier	1.0%
HPOTP Turbine Flow Multiplier	1.0%
T/C Characteristic Velocity Multiplier	0.125%
FPB Fuel Injector Resistance	1.0%
OPB Fuel Injector Resistance	1.0%
Oxidizer Pressurant Flow Rate	1.505%
LPFTP Inlet Orifice Resistance	1.0%
LPFTP Turbine Nozzle Area	1.0%
Fuel Pressurant Flow Rate	0.65%
LPOTP Pump Cavitation Correction	0.0%
HPOTP Pump Cavitation Correction	0.0%
LPFTP Pump Cavitation Correction	0.0%
HPFTP Pump Cavitation Correction	0.0%

dependent variables are normally distributed, we can write, using the algebra of normal distributions and the influence function relationships:

$$a_m = \sum d_{m,i} p^{(i-1)} \tag{8}$$

$$s_m^2 = \sum (a_m \cdot b_k \cdot COV_k)^2 \tag{9}$$

$$b_k = \sum c_{k,m,i} \cdot p^{(i-1)} \tag{10}$$

where $d_{m,i}$ is the nominal dependent variable influence coefficients, $c_{k,m,i}$ is the influence coefficient relating the independent variable k to the dependent variable m, COV_k is the coefficient of variation of the independent variable k, a_m is the mean of the dependent variable m, and s_m is the standard deviation of the dependent variable m. These equations were derived directly from the influence function equations and have been presented previously in the context of measurement error. Equations 8-10 can be used to predict exactly the variability of any normally distributed set of independent parameters in the influence functions.

The probabilistic model was run using these inputs to predict the variability in the HPFTP turbine speed. Table 12 gives the results of these calculations and Figures 30 and 31 present the results graphically. The first column gives the results when the mixture ratio was held constant at its nominal value. The second column of Table 12 gives the results when all of the variables in Table V were allowed to vary according to their respective coefficients of variation.

These calculations were performed to show the validity of equations 8-10. If equation 9 is used to predict the variance when the coefficient of variation for the mixture ratio is set equal to zero then one finds that the standard deviation is equal to 45.6, which compares exceptionally well with the model calculation of 47.0 from Table 12. The plots in Figures 30 and 31 show this difference, and they point out the dominance of the mixture ratio in determining the variability in the turbine speed.

87

The last column in Table 12 gives the mean and standard deviation for 62 tests run at 104% power. The calculated standard deviation, 341.5, should be comparable to the ANLOAD results of 147.1. The differences in these calculations are probably due to more variability in the engine than originally projected. As expected the engine balance variation in the last column of Table 12 do bound the test data results.

This work is only the initial effort at including all sources of variability in the probabilistic model and subsequent coefficients. Of course these coefficients must include some form of qualitative data, i.e. expert opinion, to account for all of the variability, yet this source of variation cannot be so "soft" so as to overwhelm the calculations being performed. Further study of the data in Table 11, and any other data that becomes available of this form, is planned to more accurately assess the differences noted and their source.

TABLE 12
VARIABILITY IN THE HPFTP TURBINE SPEED

PARAMETER	MIXTURE RATIO HELD CONSTANT	ALL VARIABLES RANDOM	TEST DATA
Mean value	35500.0	35502.5	35425.3
Computed standard Deviation	47.0	147.1	341.5
2-sigma Percentage	0.26%	0.83%	1.93%
Expert opinion	1.10%	1.10%	1.10%

Figure 30. HPFTP Turbine Speed: Mixture Held Constant

HPFTP Turbine Speed

104% Power
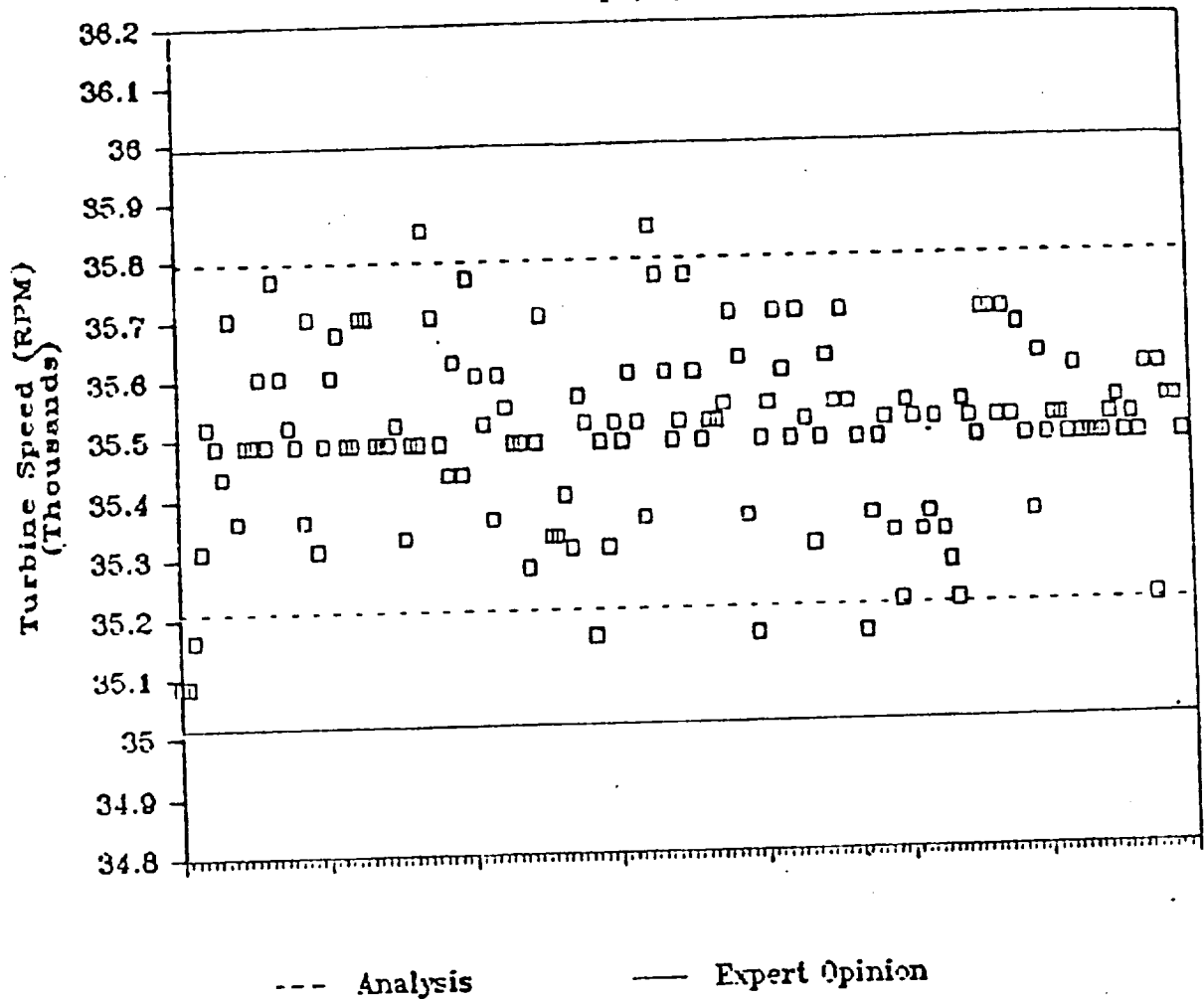
Figure 31. HPFTP Turbine Speed: All Variables Random

6.0 EXAMPLE TURBINE BLADE ANALYSIS

6.1 Introduction And Definitions

To examine the possibilities in the application of the probabilistic model discussed in the previous section, four sample problems have been constructed. The first of these examines a change in the mission profile for the SSME HPFTP turbine torque analysis, from a steady state level of 104% power to 109% power. The second example considers the changes in the SSME HPFTP turbine torque when the inlet turbine temperature is increased 10% during the 109% power level operation. The third case is performed for the SSME HPOTP turbine torque at 109% power. While it is true that this analysis also can be done based on previous data analysis, it will be performed using the probabilistic code, ANLOAD. In this way, the validity of such an approach can be examined. Finally, a prediction for the turbine torque for the turbine fuel pump in the J2 engine operating at 109% power will be examined.

6.2 SSME HPFTP Turbine Torque At 109% Power

Table 13 gives the input variable definitions for this analysis. The procedure described in Appendix A was used to set-up the input to the probabilistic program for this analysis. The RASCAL analysis was used to calculate the HPFTP turbine torque with 1000 simulation points and each input discretized into 40 intervals. The results of the analysis were a uniform distribution for the torque with a mean value of 10,824 ft-lb$_f$ and a standard deviation of 64 ft-lb$_f$. This indicates that the coefficient of variation is approximately 0.6%.

6.3 SSME HPFTP Turbine Torque: 109% & 10% Increase in Inlet Temperature

For this study, the same inputs as given in Table 13 were used -- except the mean value of the fuel inlet temperature was increased by 10%. It was assumed further that the coefficient of variation remained the same, so that

TABLE 13
STANDARD INPUTS FOR PROBABILISTIC CALCULATIONS

Variable	Type	Mean[1]	Std Dev[2]
Commanded Mixture Ratio	Uniform	5.97443	6.05108
Fuel Inlet Total Pressure	EV-I	25.2313	.173689
Oxidizer Inlet Total Pressure	Normal	64.3341	21.0374
Fuel Inlet Temperature (R)	Lognormal	3.61308	0.0162595
Oxidizer Inlet Temperature (R)	Lognormal	5.10174	7.19274E-03
HPFTP Turbine Efficiency Multi	Normal	1.009	.02018
HPFTP Turbine Flow Multiplier	Normal	1.0125	.02025
HPOTP Turbine Efficiency Multi	Normal	1.0152	.020304
HPOTP Turbine Flow Multiplier	Normal	.9741	.019482
T/C Charac Velocity Multiplier	Normal	1.004	.00251
Main Fuel Valve Resistance	Normal	.0138	.0017526
Main Oxidizer Valve Resistance	Normal	.0107	.0013589
Oxidizer Pressurant Flowrate	Normal	0.0557	0.0017267
FPB Fuel Injector Resistance	Normal	.155	.0031
OPB Fuel Injector Resistance	Normal	.685	.0137
LPFTP Inlet Orifice Resistance	Normal	.716	.01432
LPFTP Turbine Nozzle Area	Normal	.95	.019
Fuel Pressurant Flowrate	Normal	.032897	.000428

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[1]This is the lower bound for the uniform, and the shift parameter for the extreme value Type I.

[2]This is the upper bound for the uniform, and the scale parameter for the extreme value Type I.

the standard deviation was calculated based on the coefficient of variation for the fuel turbine inlet temperature given in Table 13 times the new value of the mean. The results of this calculation indicate that the distribution is still uniform, and the standard deviation is still equal to 64 $ft\text{-}lb_f$, but the mean value is now 10,937 $ft\text{-}lb_f$. Thus, the assumption that the coefficient of variation for the fuel turbine torque is independent of power level, and therefore, is independent of time, is <u>not</u> valid.

The reason for this can be seen easily by examining the model for the calculation of the torque. In the table of influence coefficients, the value of the fuel inlet temperature is not changed by simply changing the power level. Thus, while the change in the mean value will cause a change in the predicted torque value, it does not affect the variance. This is obvious from examining the equations for the influence function calculations. In equation (2b) for the fuel turbine inlet temperature, the $c_{j,i,k}$'s are equal to zero for k equal to 2, 3, and 4. Therefore, the variance contribution from changes in the fuel inlet temperature are equal to zero.

6.4   SSME HPOTP Torque Prediction From Scaling

The derivation of a scaling parameter is based on the analysis just performed. Given the calculated value of the HPFTP torque, its horsepower, and its speed, the following scale parameter is used:

$$T = 5300 * HP * P_L / RPM$$

This gives a mean prediction of 5110 $ft\text{-}lb_f$. Assuming a similar coefficient of variation gives a standard deviation of 30.7.

Using the QLM to calculate the mean and standard deviation gives values of 5083 and 35.0 $ft\text{-}lb_f$, respectively. Obviously, these are relatively accurate. Additional studies must be performed to quantify this accuracy.

6.5 J2 Fuel Turbine Torque Prediction From Scaling

Similar to the last case, the predicted value of the torque on the J2 engine would give a mean value of 1800 ft-lb$_f$. If a value for the coefficient of variation is used from the SSME HPFTP analysis, the predicted standard deviation is 11 ft-lb$_f$. However, since the J2 is a single stage engine, the variability from the inlet temperature should be reduced. Since, this contribution from the SSME HPFTP analysis is approximately 33% of the total variance, it is predicted that the standard deviation should be between 8 and 11 ft-lb$_f$.

7.0 LDEXPT: THE LOAD EXPERT SYSTEM FOR CLS

7.1 Goal and Status

The goal of the composite load spectra project is to provide a knowledge-based tool to generate and analyze composite loads of a rocket engine design and to supply them in a form that a probabilistic finite element computer program can use.

This is being accomplished by developing probability models to simulate engine performance and other loads to collect the expertise built up over the years in order to help design a new and improved rocket engine. This computer program will provide a powerful probabilistic and statistical tool to guide users to obtain probabilistic information on rocket engine component loadings and provide expertise in analyzing engine loadings probabilistically.

A knowledge-based system has the facility of building up a large domain knowledge base and maintaining a large amount of data. It has the capability to perform logical deduction and inferences and thus it can help users to make decisions and to solve problems. These characteristics allow one to build an expert system to simulate and perform the process of problem solving by an expert in a particular problem domain.

This project requires a knowledge-based system that has a built in powerful probabilistic modeling and statistics tool box and a large database of rocket engine knowledge. This knowledge-based system will help the engineer to master probabilistic modeling technology and provide probabilistic information for structural analyses. The functions of this knowledge-based system are to manage the database, provide expert knowledge in generate probability loadings for rocket engine. In addition to being able to utilize the vast amount of existing FORTRAN probability and statistics tools, the code is required to have a FORTRAN based system. There is no existing knowledge system development tool that can satisfy all the needs of this project. Therefore, it was decided early that a FORTRAN based

95

non-proprietary knowledge system will be built to suit the needs of this project.

A simple philosophy discovered by pioneering workers is that the power of a knowledge base system is in its capability to have a vast amount of domain knowledge and not necessary to have a complex inferencing engine. Following this philosophy, the load expert system LDEXPT was built with a simple inference system. This is the expert system driver controlling the rule processing and the user query interface. The expert system needs to know how to perform probabilistic modeling and statistical analysis. Therefore, a powerful probabilistic modeling and statistics tool box (consisting of FORTRAN routines) was built and is continuing to be developed. To make knowledge representation more efficient for the load expert system, a database system was implemented. This database system facilitates the communication between the expert system and the knowledge base, helps maintain data integrity and avoid data redundancy. The load expert system LDEXPT version 2.0 has all three elements in place. Its knowledge base has load information for SSME type engines, knowledge about the influence coefficient method for engine performance analysis and the turbine blade load information and scaling model calculation.

The load expert system is a rule-based expert system. The inferences are carried out with the rules. In the load expert system the rules are modularized. Each module was designed to solve a particular problem or to perform a task. The load expert system LDEXPT version 2.0 has rule modules to calculate turbine blade loads using the scaling model and to generate engine dependent loads (e.g. HPFPT discharge pressure) using the influence coefficient method. The rules designed so far are mostly related to process control and information retrieval. In the next development, rules to generate probability models for a complicated composite load spectra will be designed which will require more intelligence.

The probabilistic modeling and statistics tool box now has a stand alone load spectrum generator for steady and quasi-steady state loads. It has a statistics data analysis package which can select a best fit distribution

for a random variable and evaluate its distribution parameters. It also has a simple plotting routine to plot the duty-cycle-data profiles and a random walk plotting routine to simulate a stochastic process.

The knowledge base now has knowledge of the turbine blade loads for generating steady state and quasi-steady state load spectra. Additional load data on pressures and temperatures are ready for adding to it. The transient loads, pops and chugs and vibration loads are being developed and will be implemented as soon as the model development is complete. Knowledge on the transfer duct has been collected and rules for transfer duct load calculations can now be developed.

The basic expert system components of the load expert system LDEXPT are all in place: the expert system driver, the database system, the FORTRAN data management system and the basic probabilistic modeling and statistics tool box; that is, the main tasks of system development phase are complete. The next main task is the implementation of additional applications of the expert system to the composite load spectra project.

During the past year, the load expert system LDEXPT version 1.0 was implemented on IBM/PC and the NASA Lewis Research Center's mainframe. The IBM/PC version was implemented with MicroSoft FORTRAN. The NASA/LeRC version was in IBM VS-FORTRAN. The IBM version has no database system and no plotting. When the LDEXPT version 2.0 is checked out on the Rocketdyne's Perkin-Elmer computer, it will then be implemented onto the NASA/LeRC system. This will have the database system and the plotting utilities. In addition, it will have additional rule modules for the turbine blade loads and the transfer duct loads.

7.2 LDEXPT, The Load Expert System

A rule-based expert system casts knowledge into rules. It uses modus ponen and universal specialization to carry out the inference process. Rules are in the form of IF... THEN...which are called production. Thus, a rule-based system is also called a production system. In a pure production system, rules and control system (for searching) are in separate modules: the knowledge base and the inference engine. The knowledge base consists of the problem-solving knowledge, the process-control knowledge and the database knowledge, all in a rule-form. The function of the inference engine is to perform a chosen (built-in) searching algorithm on the knowledge (rule) base in order to reach a solution to one's problem. There are two types of searching strategies that are widely used in the rule base systems. They are the forward chaining and the backward chaining strategies. The forward chaining strategy starts from an initial problem state, searches forward until it reaches a goal state. The backward chaining strategy starts from a goal state, searches backward until it reaches the initial state. Searching forward means that rules are searched until the condition part of a rule (LHS, left hand side) matches with the present state, and then the conclusion part (RHS, right hand side) of the rule is used to move to a new state. Searching backward is just the opposite. Rules are searched until a rule is found such that the conclusion part of the rule matches the goal state. The condition part of the rule then becomes the new goal state (subgoal). This process is repeated until the initial state was reached.

The pure production system is a very powerful tool. It is most suitable to the classification problems such as diagnostics. However, when problem becomes complex and deals with multiple data types at the same time, it is difficult to maintain an uniform knowledge base and the generic nature of the inference engine slows down the inference process. When frames were introduced, the generic inferencing scheme becomes very inefficient, if not impossible.

The composite load spectra evaluation and generation is a planning and prediction problem. It has a large data base with multiple data structures

but is expected to have small number of rules for problem-solving knowledge and process-control knowledge. It needs to carry out numerous computations and it is best to branch out of the expert system to do the analysis. It is obvious that a pure production system mechanism will not be able to satisfy the needs of this program. At the time, an expert system development tool, EXTRAN, was available to us for evaluation. It was a rule base system using a decision tree inference scheme. Its rules were built into a decision tree hierarchy. Searching through the tree was carried out with user supplied information or selection. The tool was in FORTRAN, which had the advantage of a convenient integration with vast amount of the probabilistic modeling and statistics tools available for engineering. The loss of flexibility of a pure production system was not serious because the rule base for the problem-solving knowledge and the process-control knowledge of this program was expected to be not too large and rules would not be modified frequently once they were established. So the load expert system inference scheme was conceived and it was modeled after EXTRAN. There is an added benefit to have the load expert system compatible with EXTRAN. EXTRAN is used at Rocketdyne to develop expert systems for engine performance analysis and high frequency data analysis. These different programs could benefit each other by using similar expert system development tools.

The load expert system for the composite load spectra project, named LDEXPT, has the rules built in a decision tree routine or several routines if the rules can be decoupled. In this way, the rules are modularized. The load expert system communicates with users via a problem text files, where questions for query are stored. The system records the process so that it can show them to the user when a "HOW" is asked. User can also ask "WHY" a question is prompted and the load expert system will reveal the logics behind the question.

The load expert system LDEXPT version 1.0 was built with the scheme described above. A very simple consultation system was built and demonstrated the feasibility of the design. However, the system needed a lot of help from users in the following ways. Many redundant queries had to be made to obtain information which could be identified with one or two

attributes (attribute is a characteristics or property of the group of information). Redundant information had to store in many places so that it could be retrieved by different rules. This in turn made maintenance more difficult and decreased data integrity. An obvious solution was to have a structure knowledge base where data were built into databases. The most general database structure that could be constructed for any data type was the relational database. With a structure knowledge base, data integrity could be easily maintained and data redundancy could be avoided. Therefore, a database system was built into the load expert system LDEXPT version 2.0. The load database system was modeled after a relational database management system except that the relational algebra operations were not built. These operations concern with merging databases, combining them etc. When they are needed in the future they will be built as database utility program.

The load expert system LDEXPT (version 2.0) has two main modules: the rule base management system (RBMS) and the knowledge base management system (KBMS). The RBMS consists of the expert system driver (SESUIM), the rule base module and the load generation module (ANLOAD, developed by Battelle). The KBMS has the load database system and the duty-cycle-data processing and FORTRAN I/O module. A statistics and load probabilistic modeling tool box is being built slowly. This tool box concept is consistent with the expert system concept in that it provide user with expert tools in doing data analysis and modeling. The tool box will heavily employ routines in ANLOAD and the data analysis package AWESUM provided by BATTELLE. Figure 32 shows the overall structure of LDEXPT. Although the database system is included under the KBMS, the interaction between it and the expert system is extensive. The load generation module ANLOAD could be included in the load probability modeling tool box. It was not done because ANLOAD can be implemented as a stand alone program to perform calculation in batch mode environment.
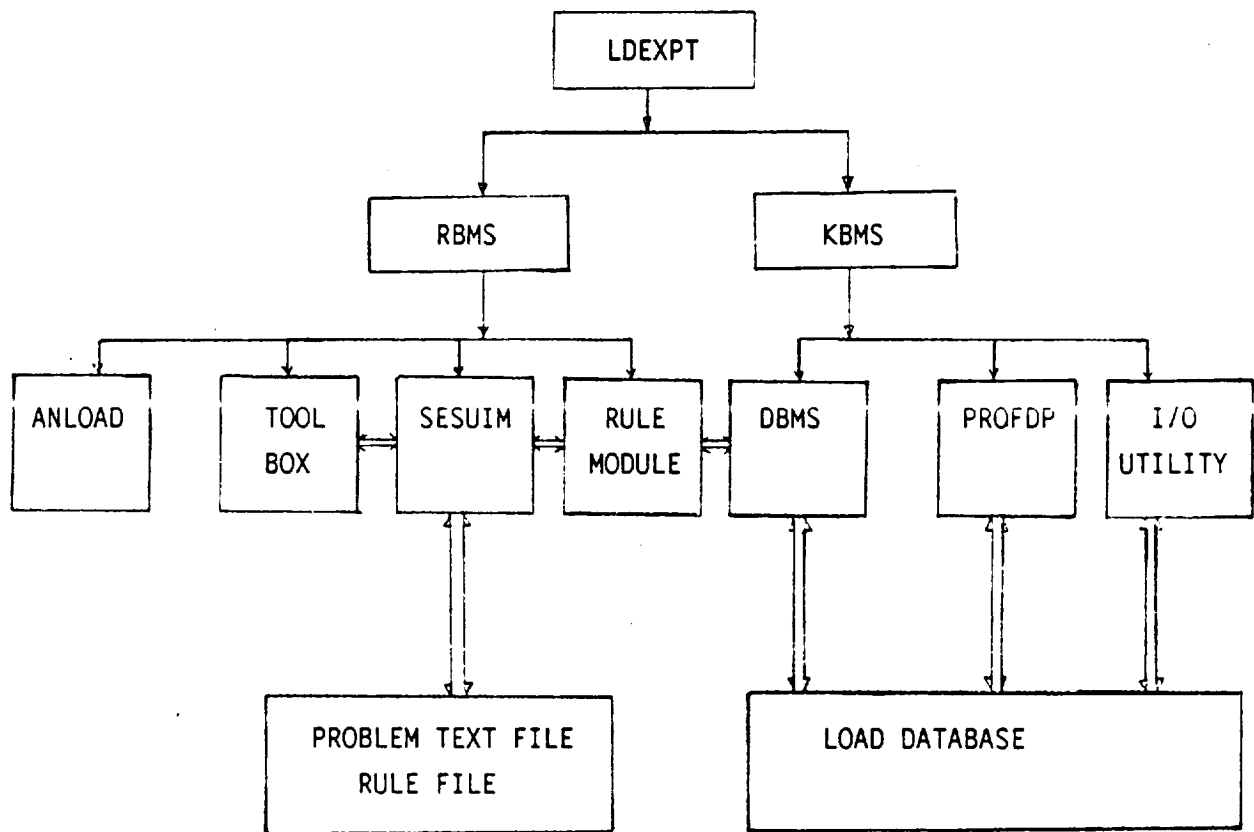
Figure 32. LDEXPT: Load Expert System

7.3   Implementation of the Load Database System and Interface

The engineering data in LDEXPT version 1.0 was organized in a conventional data file format. This format was found to cause data redundancy problems, which the expert system could not handle. For example, if a test-data ID number was identified, the engine type and mission history profile type were determined (known to our engineers). However, the expert system would require additional specific rules to identify these relations. This redundancy problem not only complicated the system but also resulted in an exponential growth in the number of rules required for the expert system. This problem could be resolved if the engine type and the mission type were built into a property list of the test-data ID as could be done in LISP or if the three attributes were built into a database, e.g. a relational database. Using test-data ID as a key, once it was identified, the engine type and the rest of the properties were determined. The expert system did not need to query further to acquire other information.

Organizing data into a database model has many advantages. The obvious ones are avoidance of data redundancy and inconsistency, ease of enforcing data integrity and ease of data maintenance. A database model of engine data also has the side benefit of a well organized data base and an easy to understand retrieval system. Moreover, the most important advantage of building a database is that it facilitates the communication between the expert system and the engineering data base, which in turn speeds up the knowledge acquisition process for the load expert system.

A Relational Database Model. A relational database model is like a table of key variables and attributes. The keys are used to identify a record (row) in the database model (table). The values of the keys are unique to each record. In database terminology, the model is in normal form. For the load database, for example, a database table LOAD could be built which has the following fields (columns):

LOAD-ID, LOAD-name, Mean, COV, Dist-type, NE-coeffs

where LOAD-ID is the key,
       LOAD-ID is the load ID number
       LOAD-name is the load variable name, e.g. mixture ratio
       Mean is the default mean value of the load at 100% power
       COV is the coefficient of variation of the load
       Dist-type is the default distribution type of the load
       NE-coeffs is the inference coefficients for calculating
          the nominal engine mean value of the load at the desired
          power level

With this database table, once the load ID is identified, the mean of the
load, the COV and the rest of information can be easily accessed by the
expert system.

A second example is the Duty-Cycle-Data table:

Test/Flight-ID, Load-ID, Engine-type, Mission-type, Duty-Cycle-Data

where Test/Flight-ID and Load-ID are the keys
      Test/Flight-ID is the test data ID or flight data ID
      Load-ID is the independent load ID
      Engine-type is the engine type, e.g. SSME
      Mission-type is the mission history profile type, e.g.
         acceptance test
      Duty-Cycle-Data is the group-name of the duty cycle data
         stored in the data file

There are a total of five databases built for calculating the turbine blade
component load spectra: LDIP, LDEP, INFC, LTBC and DFAT. They are listed
in tables X.1 to X.5 of Appendix B (for INFC, only samples are listed
because of its large size). The database description of the five tables are
also listed in Appendix B.

103

The three databases LIDP, LDEP and LTBC belong to the same class of the object LOAD, which possesses the following attributes: load-ID, load name, mean, coefficient of variation (COV), P3 (rare event probability limit), distribution-type, and a set of coefficients for its nominal engine configuration. In the load databases, the mean values for the loads are values for the nominal engine configuration. The COV's and their distribution type for mixture ratio, fuel inlet pressure and temperature, and LOX inlet pressure and temperature are values based on engine data. The COV's for the rest of the independent loads and all of the dependent loads are values based on expert opinion and the SSME engine balance model. The distribution type for all other loads was assumed to be normal. The nominal engine coefficient sets were obtained from the influence coefficient file "INFLUENCE.DAT". These entries, that is the mean, the COV etc., for the turbine blade component load are not available at this time. When default values are available, they will be stored into the LTBC database.

The INFC database has sixteen (16) tables. Each table includes information for four dependent loads. For example, the first table has influence coefficient set and gains for dependent load 1 to 4, the second table is for dependent loads 5 to 8 and so on. an independent load. The attributes for INFC are the dependent load-ID, the independent load-ID, the influence coefficient set (4 numbers) and the gain set (4 values). The influence coefficient sets were obtained from the influence coefficient file. The gain set includes GAIN65 (gain for 65% power level), GAIN90 (gain for 90% power level), GAIN100 (gain for 100% power level) and GAIN104 (gain for 104% power level). These gains were calculated based on the assumption of normal distribution for the independent load and using the COV values from the independent load database LIDP. The idea of including a gain set covering the operating range of power level is significant. By examining the values of the gain set, one could easily spot which dependent load gain was significantly contributed to by the independent load. This kind of expert knowledge can now be built into the load expert system thanks to the database system. Here we have learned an important lesson that is: the knowledge representation of the domain knowledge is very important to the success of this project.

Database Design. A relational database model is being built for LDEXPT. An indexed sequential access method (ISAM) algorithm is employed for retrieval of database records. A key file is constructed for each database table. The keys are sorted in certain order. The records are then retrieved through the index stored in the key file uniquely identified by the values of the keys. There are physically two files for each table, a data file contains all records of data and a key file contains values of all the keys. In this model, no secondary keys are allowed. The different key variables in the key file are variables of a primary split key, all values of the split key variables must be identified uniquely for a record retrieval.

Functions identified for the database system are CREATE a table, UPDATE a table, DELETE a record, SELECT a record, BUILD a key file and SAVE a table. The detail function of each procedure is presented below.

CREATE a table:
  Set up data dictionary: record description: # of field, # of keys;
                          field description: field-name, data-type;
  Enter data records;
  BUILD a key file;
  Save the database.

READ data dictionary:
  Open a database file and locate the desired database table;
  Read data dictionary (i.e. field-names or key-names of the table);
  Move database table data on-line.

UPDATE a table:
  Enter a new record;
  Sort the new record key(s) into the key file;
  Save the database (optional).

105

DELETE a record:
  Delete the record key value(s) from the key files;
  Mark the delete data record in the table.

SELECT record(s):
  Retrieve data record index/indices from the key files;
  Display the record(s).

BUILD a key file:
  Create a key file;
  Sort the key value(s).

SAVE a database table:
  Select SAVE option;
  Save the database table.

A very efficient algorithm for building an ISAM key file is B-tree. However, because there is no pointer data type and no recursion in FORTRAN, it is difficult to build a B-tree, in fact any tree. For now, a sorted array will be used as our key file format.

The database functions being built for LDEXPT are similar to those identified above. The available database commands and the database routine descriptions are presented in Appendix B.

Database Limitation. For the moment, the database model is limited to 15 fields, 10 (split) keys and 100 records. Each field of character type is limited to 8 characters long.

Keys are only of character or integer type. These limits were chosen based on the needs of LDEXPT and they can be expanded easily if they do not become too large. For building large size database, this model has to be modified and the limitation of using FORTRAN language to build a database will severely hinder the effort. Other languages such as C would be more suitable for that purpose.

The main purpose of this database system is to enable one to write rules to retrieve knowledge for the expert system. Hopefully this knowledge can be modeled with many small relational database tables. Normalized relational databases tend to be comprised of small tables. Knowledge in this form will be easier to be understood by engineers who have to sort out large volume of data.

Interface. Communication between the expert system driver and the database system is achieved by putting an expert system option into the database routines. The interface allows the expert system driver to query only the key attributes and to retrieve data items from a database. Two interface routines GRSPRC and GRSPMN were written. GRSPRC grasps (retrieves) a database record and stores it in the array ITEMS. GRSPMN grasps an item in a database record. These two generic data retrieval routines send the desired data items to the rule base system for processing.

The implementation of the database system is a significant development for the load expert system LDEXPT. With appropriate representation, the text book knowledge and expert's knowledge can be incorporated in the knowledge base to make LDEXPT into an intelligent load expert system.

7.4 LDEXPT's Rules and Implementation

The domain knowledge for the composite load spectra (CLS) project consists of two main areas: the probabilistic modeling method and the rocket engine structural load information and calculation. The synergism of the two domains have to be brought about to produce the domain knowledge for CLS.

Knowledge acquisition is the key for building a successful expert system. The rocket engine domain knowledge covers a broad range of information: rocket engine component geometric information and operating condition, rocket engine measurement such as engine performance data and power spectral distribution, rocket engine structural load models etc. There is a rich pool of information built up from the last several decades. Some are in notebook form, others are in textbooks, and many of them are measured data stored in data files, in LOTUS files or simulated in models such as the engine balance model and the influence coefficient model. There is also a vast amount of knowledge built up over the years in the rocket engine specialists minds. Many of these expertises are not documented anywhere. This knowledge is being derived from specialists at Rocketdyne. We are consulting with specialists who work on the on-going SSME data collection and evaluation tasks to supply data information relevant to this project. We find out how experts use models to simulate engine performance. All these have to be built into an uniform framework so that the expert system can utilize them effectively. The framework for storing knowledge is another key for building a successful expert system.

The probabilistic modeling is the other important knowledge domain for the CLS project. It includes modeling random variables, simulating stochastic processes, data statistical evaluation and many more. Battelle's expertise in this area is being used to help build models to simulate composite load spectra. Most of these knowledges are in algorithmic forms and could be built into computational procedures. The remaining problem is of course that how does the expert system communicate and utilize these procedures.

All the knowledges relevant to the load expert system come in three basic types: text information, engineering data and modeling algorithm. Rules are designed to represent the textual information needed for load generations. Rules also are written to control the computation process and to retrieve and manage the requested engineering data. For the load expert system LDEXPT, rules are separated into rule modules to perform specific tasks. Interactions between different rule modules are controlled by other modules which employ a simple working memory model to communicate between them. The model will be improved throughout the project.

The Working Memory Model. The working memory model was designed for passing information (short-term memory) between different rule modules. To keep the model simple, the information saved was limited to that needed to pass from one module to another module but not between multiple rule modules. The working memory consists of a "stack" and a memory array. The "stack" is used for storing database indices for record retrieval and the memory array is used for storing information (e.g. subgoals, facts).

The advantage of implementing a working memory model is that many inference processes can proceed without user intervention. For example, suppose a turbine blade HPFTP centrifugal load spectrum calculation was requested. The load expert system would first find out what dependent load(s) was needed and the associated scaling model coefficient from the turbine blade load database. In this case, it was the HPFTP turbine speed. This information was stored in the working memory and passed to the dependent load rule module. There the expert system retrieved the dependent load information and the associated nominal engine coefficient sets. Then, the expert system began to select the independent loads with the help of another rule module. The dependent load ID's were passed from the dependent load rule module. The expert system then selected a number (as requested by user) of independent loads which had the most contribution to the turbine speed load. Without the working memory, user has to supply this information between modules in order to complete the process.

LDEXPT's Rules. The rule base for the load expert system LDEXPT was redesigned since the implementation of the database system. The rule base is composed of rule modules. Each rule module is an independent unit and has its own database table(s) associated with it. Using rule modules as building blocks allows incremental development of a rule base for the expert system.

The following examples are two of the rule modules implemented.

Rule module for load data base:

    If   the load ID is number N
    then its name is AAAA,
         its mean is M
         its standard deviation is SIGMA,
         its P3 (rare event probability) is ZERO or a fraction,
         its nominal engine coefficients are A1, A2, A3, and A4.

Rule module for Influence Coefficient Model:

a) If   the dependent load ID is M and
         the independent load ID is N
    then the influence coefficient parameter set is C1, C2, C3 and C4.

b) If   the dependent load ID is N and
         the user requests that the expert system selects the M most
         influential independent loads on the dependent load and
         the selection is going to be based gain for power level X
    then the M independent loads are M1, M2....

c) If   the dependent load ID is N and
         the user requests a simple deterministic influence
         coefficient model calculation
    then the expert system will either request user to select the
         independent loads manually or the expert system will select them,

retrieve influence coefficient set and
perform the deterministic influence coefficient model
calculation.

Nine rule modules were implemented. These include rule modules for the load database, the duty-cycle-base, the influence coefficient model, the quick look model and the turbine blade load scaling model. Their rules are listed in Appendix C.

More rule modules will be designed and built. It can be seen that the load expert system now possesses good knowledge about rocket engine loads of which some data (e.g. most of the load's standard deviations) are based on the expert's estimates. The load expert system also possesses good knowledge on the influence coefficient model and the turbine blade component load scaling model and will include the information on the other three components as the system progresses. It even shows signs of intelligence in being able to select the most influential independent loads for a dependent load calculation.

There is no new information supplied to the expert system to enable it to select independent loads for the users. The information is in the data file INFLUENC.DAT (the data file used to perform influence coefficient model calculations). However, if one looks at the data file, one sees lines and lines of numbers. It is very difficult to extract any information out of it. After processing it and putting it into a load database, the information becomes alive. Simply by sorting the gain values that were built into the database, the expert system is able to select the most influential independent loads for a dependent load calculation. The point is that an appropriate knowledge representation is very powerful. The database implementation to the load expert system proves to be a very significant contribution to this development. The database and the rule modules from our load expert system together look very much like the frames used in the frame-based knowledge system. However the object programming paradigms such as inheritance and class so prominent in a frame-based system are not seen in our system.

The rules designed so far are mostly related to process control and information retrieval. As we acquire more and more expertise on how an expert solves a composite load spectra problem, we will build rules to carry out the induction process of the experts and in so doing increase the intelligence of the load expert system.

7.5 LDEXPT Future Development

The new version of the load expert system LDEXPT (version 2.0) is not yet fully tested. Different consultation sessions will be run to verify the correctness of the rule modules implemented. In the coming months, transient model and nonstationary stochastic algorithm will be implemented. More rules for turbine blades, transfer ducts, lox posts and the HPOTDD will be added. The pops, chugs and vibration data will be transformed into databases and stored in the load knowledge base. Probabilistic models for generating pops, chugs and vibration loads will be provided in the load expert system.

The basic elements of the load expert system are all in place. The main task now is knowledge engineering. This involves designing representation for the vast amount of engine data, implementing the process-control knowledge and learning the problem-solving knowledge from experts and translating it into rules. As mention earlier, the two major knowledge domains for the composite load spectra problem are the rocket engine analysis and design, and the probabilistic modeling of loads. The experts from Rocketdyne and Battelle are relied upon to acquire the knowledge. Engine data and load information are analyzed and cast into a convenient form such that the load expert system can utilize them to perform intelligent tasks. Rules for the problem-solving knowledge need to be identified and implemented.

The way the load expert system was set up requires that a knowledge engineer who is familiar with the system maintains the expert system. New knowledge and learning are added to the system manually by the knowledge engineer.

The procedure is not difficult. It needs to put the new data into a database and to write new rule module (FORTRAN) routines, compile them and link into the load expert system. However, the knowledge engineer has to check the consistency of the new database with the existing ones, avoid implementing redundant data. He should also beware of any conflicts between rule modules and try to resolve them. Only then a sound expert system is maintain as it grows larger and more intelligent.

8.0 References

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APPENDIX A

PROBABILISTIC MODEL DRIVEN CODE FOR STAND ALONE OPERATION

There are two primary computer programs for executing the probabilistic load model: (1) a BASIC program (MENU) for assisting in generating input and displaying the results of the probabilistic load; and (2) a FORTRAN program (ANLOAD) for performing the actual probabilistic load calculations. The steps for executing these programs are discussed below

A program, MENU, has been written in BASICA that performs two functions. First it is used to generate an input file for use with the ANLOAD program. This is a menu driven program that writes an output file to a floppy disk which is subsequently used as input to ANLOAD. The second function of MENU is to display the results of the ANLOAD calculations.

To illustrate the use of these programs, the sample problem used is the one discussed in last year's annual report. In this example there are six stochastic loads which are all stationary. The object is to calculate the mass flow rate in the HPFTP and the HPFTP shaft speed. Each of these quantities are combinations of four other, individual loads.

To begin the session the IBM is turned on and the following commands are entered. It is assumed throughout the discussion that at least two disk drives are available.

    C> GRAPHICS
    C> BASICA NEWMENU

The MENU program is now operating. To use the MENU there are two important keys – the function key F1 and the cursor down arrow. Simply stated the F1 key can be thought of as a negative response (reject the option) while the cursor down key is a positive response (accept the option). The first

115

message on the screen is a "billboard" message. A billboard message does not require a response but rather is simply providing information to the user. Striking the F1 key will cause the next menu to printed.

The first message informs the user that the program does perform two different functions; either input preparation or display the load model calculational results. After striking the F1 key the program asks that one of these two functions be selected. Since we are interested in preparing a load model, run the first option is selected by striking the cursor down arrow.

The next message lists all of the possible engine parameters and individual loads currently programmed. To include one of these variables in the calculation, the cursor down key is used; to not include one the F1 function key is used. When all variables have been selected the F3 function key is pressed.

The next screen lists the selection and asks if the list is correct. If it is the cursor down key is used, if not the F1 key will return the user to the previous menu.

The next menu asks which of the three probabilistic models is to be used for the current calculation and, then, if it is desired to use medium or high accuracy.

The next set of menus allows the user to define the probabilistic form for each of the input variables. By pressing the F3 function key first the user requests that default variables be used. Otherwise, the cursor down and F1 function keys work as usual. The program then lists the input and allows the user to accept or reject it before proceeding to the next variable.

At this point all of the necessary data for the independent variables has been selected. The next menu lets the user select the dependent variables which he wishes to include in the analysis. The current dependent variables

are listed and the cursor down and F1 keys are used to select or reject the variables on the list. The F3 key lets the program know that the selection process is finished. After the F3 key is used, the program lists the dependent variables to be included in the analysis and allows corrections to be made if there is an error in the list.

Next, for each dependent variable the list of independent variables included in this analysis is presented on the menu. The cursor down key is used to select the variables from this list which are variable for the specific dependent variable being shown. The F1 key deletes that independent variable from the input to the current dependent variable, and that variable only. If the independent variable is not to be included for subsequent analyses it must be deleted later.

The next menu asks if there are any rarely occurring loads which would be added as "spike" type loads. If there are, the frequency of such loads is requested as well as what its form is.

Finally the program requests information on the mission phase history. For the initial phase the type (transient, quasi-steady, or steady), its start time and the power level at this time, and its end time and power level are requested. Subsequent requests will not request the start time since it is assumed to be a continuous process in time.

After all of this information has been collected, it is stored in a file named ANLOAD.DAT. This file can then be input directly to the FORTRAN program for analysis.

A sample input is shown in Table A-1.

117

```
5
1
2
4
1  2  3  4
0
100  1  5  999999
2
50  50
HPFTP Turbine Speed
Commanded Mixture Ratio
1  5.97443  6.05108  0
Fuel Inlet Total Pressure
2  28.5545  7.38417  0.001
Oxidizer Inlet Total Pressure
2  64.3341  21.0374  0.001
Fuel Inlet Temperature (R)
3  3.61308  .0162595  0.001
Oxidizer Inlet Temperature (R)
3  5.10174  7.19274E-03  0.001
4  3       0        0        0       .05
1          0        .65      .05     5
2          39000    500
2          2.5      .1
2          .65      1.04     5       20
3          1.04     1.04     20      100
100
```

APPENDIX B

THE LDEXPT LOAD DATABASE DESCRIPTION AND EXAMPLES

LIDP : independent load database table group name

FIELD NAME	DESCRIPTION
LIDP-ID (key)	independent load ID
LD-NAME	load name
MEAN	nominal engine mean value of the load or any predetermined default mean value
COV	default coefficient of variation
P3	rare event probability limit
DIST	distribution type
NE-COEF1	nominal engine coefficient, 0th order
NE-COEF2	1st order
NE-COEF3	2nd order
NE-COEF4	3rd order

LDEP : dependent load database table group name

FIELD NAME	DESCRIPTION
LDEP-ID (key)	dependent load ID
LD-NAME	load name
MEAN	nominal engine mean value
COV	default coefficient of variation
P3	rare event probability limit
DIST	distribution type
NE-COEF1	nominal engine coefficient
NE-COEF2	same as above
NE-COEF3	same as above
NE-COEF4	same as above

119

INFC : influence coefficient database table group name

FIELD NAME	DESCRIPTION
LDEP-ID (key)	dependent load ID
LIDP-ID (key)	independent load ID
INFL-C1	0th order coefficient of the influence coefficient set
INFL-C2	1st order coefficient
INFL-C3	2nd order coefficient
INFL-C4	3rd order coefficient
GAIN65	unit gain for power level at 65%
GAIN90	unit gain for power level at 90%
GAIN100	unit gain for power level at 100%
GAIN104	unit gain for power level at 104%

LTBC : turbine blade component load database group name

FIELD NAME	DESCRIPTION
TB-C-ID (key)	turbine blade component ID
TB-LD-ID (key)	turbine blade component load ID
TB-LD-NA	turbine blade component load name
MEAN	default mean value
COV	default coefficient of variation
P3	rare event probability limit
LD-TYPE	T/B component load type, e.g. point, distributed or nodes
LDEP1-ID	dependent load for scaling model calculation
LDEP2-ID	dependent load for scaling model calculation
SC-COEF	scaling model coefficient set to zero if more than one coefficients required
TBC-GRPN	T/B scaling coefficient file group name

DFAT : SSME flight and test duty-cycle-data file group name

FIELD NAME	DESCRIPTION
DCD-ID (key)	SSME flight or test data ID
LIDP-ID	independent load ID
	set to zero for engine power duty-cycle-data
ENGINE	engine type
MISSION	mission history profile type
	e.g. flight or acceptant test etc.
DCD-GRPN	duty-cycle-data file group name

TABLE B.1

LIDP: INDEPENDENT LOAD DATABASE

LIDP-ID	LO-NAME	MEAN	COV	P3	DIST	NE-COEF1	NE-COEF2	NE-COEF3	NE-COEF4
1	MR	0.60000E+01	0.20000E-02	0.00000E+00	UNIFORM	0.60000E+01	0.00000E+00	0.00000E+00	0.00000E+00
2	F-PI	0.30000E+02	0.25900E+00	0.00000E+00	EV-1	0.30000E+02	0.00000E+00	0.00000E+00	0.00000E+00
3	O-PI	0.10000E+03	0.32700E+00	0.00000E+00	NORMAL	0.10000E+03	0.00000E+00	0.00000E+00	0.00000E+00
4	F-TI	0.37000E+02	0.16000E-01	0.00000E+00	LOGNORM	0.37000E+02	0.00000E+00	0.00000E+00	0.00000E+00
5	O-TI	0.16400E+03	0.11000E-01	0.00000E+00	LOGNORM	0.16400E+03	0.00000E+00	0.00000E+00	0.00000E+00
6	HF-TB-EM	0.10090E+01	0.10000E-01	0.00000E+00	NORMAL	0.10090E+01	0.00000E+00	0.00000E+00	0.00000E+00
7	HF-TB-FM	0.10125E+01	0.10000E-01	0.00000E+00	NORMAL	0.10125E+01	0.00000E+00	0.00000E+00	0.00000E+00
8	HO-TB-EM	0.10152E+01	0.10000E-01	0.00000E+00	NORMAL	0.10152E+01	0.00000E+00	0.00000E+00	0.00000E+00
9	HO-TB-FH	0.97409E+00	0.10000E+00	0.00000E+00	NORMAL	0.97409E+00	0.00000E+00	0.00000E+00	0.00000E+00
10	TC-CVM	0.10004E+01	0.10000E-02	0.00000E+00	NORMAL	0.10004E+01	0.00000E+00	0.00000E+00	0.00000E+00
11	MFV-R	0.13800E-01	0.64000E-01	0.00000E+00	NORMAL	0.13800E-01	0.00000E+00	0.00000E+00	0.00000E+00
12	MOV-R	0.10700E-01	0.88000E-01	0.00000E+00	NORMAL	0.10700E-01	0.00000E+00	0.00000E+00	0.00000E+00
13	CCV-R	0.10000E+01	0.10000E+01	0.00000E+00	NORMAL	-0.19429E-15	0.10000E+01	0.00000E+00	0.00000E+00
14	FPB-F-IR	0.15500E+00	0.10000E+00	0.00000E+00	NORMAL	0.15500E+00	0.00000E+00	0.00000E+00	0.00000E+00
15	OPB-F-IR	0.68500E+00	0.10000E+00	0.00000E+00	NORMAL	0.68500E+00	0.00000E+00	0.00000E+00	0.00000E+00
16	LF-TB-OR	0.71600E+00	0.10000E+00	0.00000E+00	NORMAL	0.71600E+00	0.00000E+00	0.00000E+00	0.00000E+00
17	LF-TB-NA	0.95000E+00	0.10000E+00	0.00000E+00	NORMAL	0.95000E+00	0.00000E+00	0.00000E+00	0.00000E+00
18	O-PRS-FL	0.55695E-01	0.15000E+00	0.00000E+00	NORMAL	0.36669E+02	-0.99669E+02	0.90168E+02	-0.27112E+02
19	F-PRS-FL	0.16206E+00	0.65000E-01	0.00000E+00	NORMAL	0.16767E+00	0.17642E-01	-0.31119E+00	0.00000E+00
20	LO-PH-CC	0.10000E+01	0.10000E-02	0.00000E+00	NORMAL	0.10000E+01	0.00000E+00	0.00000E+00	0.00000E+00
21	HO-PH-CC	0.10000E+01	0.10000E-02	0.00000E+00	NORMAL	0.10000E+01	0.00000E+00	0.00000E+00	0.00000E+00
22	LF-PH-CC	0.10000E+01	0.10000E-02	0.00000E+00	NORMAL	0.10000E+01	0.00000E+00	0.00000E+00	0.00000E+00
23	HF-PH-CC	0.10000E+01	0.10000E-02	0.00000E+00	NORMAL	0.10000E+01	0.00000E+00	0.00000E+00	0.00000E+00

TABLE B.2

LDEP: DEPENDENT LOAD DATABASE

LDEP-ID	LD-NAME	MEAN	COV	P3	DIST	NE-COEF1	NE-COEF2	NE-COEF3	NE-COEF4
1	HO-TB-SP	0.27098E+05	0.52000E-02	0.00000E+00	NORMAL	0.55834E+04	0.20905E+05	0.61012E+03	0.00000E+00
2	HF-TB-SP	0.34625E+05	0.55000E-02	0.00000E+00	NORMAL	0.15410E+05	0.16751E+05	0.24632E+04	0.00000E+00
3	HO-PM-PO	0.41075E+04	0.89000E-02	0.00000E+00	NORMAL	0.14544E+03	0.24759E+04	0.18903E+04	-0.40409E+03
4	HF-PM-PO	0.61998E+04	0.90000E-02	0.00000E+00	NORMAL	0.14515E+04	0.23857E+04	0.23626E+04	0.00000E+00
5	OPB-CH-P	0.50592E+04	0.12900E-01	0.00000E+00	NORMAL	-0.25803E+03	0.44060E+04	0.48415E+03	0.42709E+03
6	FPB-CH-P	0.49555E+04	0.13700E-01	0.00000E+00	NORMAL	-0.10327E+04	0.75249E+04	-0.35029E+04	0.19661E+04
7	ENG-O-FL	0.89435E+03	0.62000E-02	0.00000E+00	NORMAL	0.10448E+01	0.89777E+03	-0.44630E+01	0.00000E+00
8	ENG-F-FL	0.14906E+03	0.69000E-02	0.00000E+00	NORMAL	0.54315E+00	0.14848E+03	0.37899E+00	-0.34476E+00
9	ENG-THRU	0.47107E+06	0.50000E-02	0.00000E+00	NORMAL	0.10474E+04	0.46729E+06	0.38848E+04	-0.11461E+04
10	O-PRS-FL	0.16206E+01	0.15000E-01	0.00000E+00	NORMAL	0.16767E+00	0.17642E+01	-0.31119E+00	0.00000E+00
11	F-PRS-FL	0.70031E+00	0.65000E-02	0.00000E+00	NORMAL	0.34437E-01	0.63776E+00	0.28114E-01	0.00000E+00
12	OPB-O-VP	0.65025E+00	0.14700E-01	0.00000E+00	NORMAL	0.61621E+00	-0.40203E+00	0.43606E+00	0.00000E+00
13	FPB-O-VP	0.78974E+00	0.13500E-01	0.00000E+00	NORMAL	0.69291E+00	-0.15036E+00	0.24719E+00	0.00000E+00
14	MCC-O-IP	0.35372E+04	0.86000E-02	0.00000E+00	NORMAL	0.78808E+02	0.27181E+04	0.95671E+03	-0.21637E+03
15	MCC-O-IT	0.19024E+03	0.20000E-02	0.00000E+00	NORMAL	0.16512E+03	0.12433E+02	0.14775E+02	-0.20906E+01
16	HG-IP	0.32438E+04	0.64000E-02	0.00000E+00	NORMAL	-0.13722E+03	0.36198E+04	-0.50439E+03	0.26555E+03
17	MCC-IEP	0.30060E+04	0.58000E-02	0.00000E+00	NORMAL	-0.16085E+03	0.30060E+04	0.00000E+00	0.00000E+00
18	HO-PM-PI	0.37915E+03	0.22800E-01	0.00000E+00	NORMAL	0.11393E+03	0.33464E+03	-0.21946E+02	-0.47482E+02
19	HF-PM-PI	0.20900E+03	0.26300E-01	0.00000E+00	NORMAL	0.26705E+03	-0.15416E+03	0.96111E+02	0.00000E+00
20	PB-PM-PO	0.70920E+04	0.98000E-02	0.00000E+00	NORMAL	-0.53504E+03	0.67636E+04	0.86343E+03	0.00000E+00

Hit any key to continue

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LDEP-ID	LD-NAME	MEAN	COV	P3	DIST	NE-COEF1	NE-COEF2	NE-COEF3	NE-COEF4
21	HO-PM-TI	0.16943E+03	0.60000E-03	0.00000E+00	NORMAL	0.16478E+03	0.28248E+01	0.24169E-01	-0.59064E+00
22	HO-PM-TO	0.19024E+03	0.20000E-02	0.00000E+00	NORMAL	0.16512E+03	0.12433E+02	0.14775E+02	-0.20906E+01
23	HF-PM-TO	0.95571E+02	0.11400E-01	0.00000E+00	NORMAL	0.60135E+02	0.19283E+02	0.16152E+02	0.00000E+00
24	MFV-TO	0.96151E+01	0.11400E-01	0.00000E+00	NORMAL	0.59801E+02	0.20174E+02	0.16176E+02	0.00000E+00
25	PB-PM-TO	0.20306E+03	0.25000E-02	0.00000E+00	NORMAL	0.16959E+03	0.15697E+02	0.17775E+02	0.00000E+00
26	HF-PM-TI	0.42210E+02	0.19000E-02	0.00000E+00	NORMAL	0.43963E+02	-0.46672E+01	0.29147E+01	0.00000E+00
27	LO-TB-SP	0.50366E+04	0.80000E-02	0.00000E+00	NORMAL	0.17100E+04	0.36940E+04	-0.36734E+03	0.00000E+00
28	LF-TB-SP	0.14921E+05	0.90000E-02	0.00000E+00	NORMAL	0.13081E+05	-0.45278E+04	0.63678E+04	0.00000E+00
29	HO-TB-TO	0.12890E+04	0.27400E-01	0.00000E+00	NORMAL	0.54480E+03	0.62070E+03	0.12346E+03	0.00000E+00
30	HF-TB-TO	0.17029E+04	0.19300E-01	0.00000E+00	NORMAL	0.14807E+04	-0.16428E+03	0.38645E+03	0.00000E+00
31	OPB-O-VR	0.13143E+03	0.98200E-01	0.00000E+00	NORMAL	0.35530E+04	-0.59476E+04	0.27260E+04	0.00000E+00
32	FPB-O-VR	0.92308E+01	0.15550E+00	0.00000E+00	NORMAL	0.14670E+03	-0.23255E+03	0.95081E+02	0.00000E+00
33	O-PRS-P	0.33703E+04	0.92000E-02	0.00000E+00	NORMAL	0.19042E+03	0.20081E+04	0.15816E+04	-0.40989E+03
34	F-PRS-P	0.33486E+04	0.79000E-02	0.00000E+00	NORMAL	0.29694E+03	0.26389E+04	0.41269E+03	0.00000E+00
35	O-PRS-T	0.83918E+03	0.24500E-01	0.00000E+00	NORMAL	0.26014E+03	0.53012E+03	0.48920E+02	0.00000E+00
36	F-PRS-T	0.47628E+03	0.12500E-01	0.00000E+00	NORMAL	0.33444E+03	0.33432E+03	-0.19248E+03	0.00000E+00
37	LO-PM-SP	0.80451E+04	0.10000E-01	0.00000E+00	NORMAL	0.23949E+03	0.68697E+04	0.93589E+03	0.00000E+00
38	LF-PM-SP	0.18573E+05	0.10000E-01	0.00000E+00	NORMAL	0.80230E+04	0.18191E+04	0.87307E+04	0.00000E+00
39	HO-PM-SP	0.11258E+01	0.18500E-01	0.00000E+00	NORMAL	-0.14279E+04	0.11165E+05	-0.39312E+04	0.25960E+04
40	HF-PM-SP	0.64475E+04	0.24000E-01	0.00000E+00	NORMAL	-0.13590E+03	0.65834E+04	0.00000E+00	0.00000E+00

Hit any key to continue

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LDEP-ID	LD-NAME	MEAN	COV	P3	DIST	NE-COEF1	NE-COEF2	NE-COEF3	NE-COEF4
41	MCC-C-PO	0.48950E+04	0.10800E-01	0.00000E+00	NORMAL	0.96970E+03	0.23960E+04	0.15293E+04	0.00000E+00
42	MCC-C-TO	0.49091E+03	0.12200E-01	0.00000E+00	NORMAL	0.34914E+03	0.33369E+03	-0.19193E+03	0.00000E+00
43	LO-TB-TQ	0.15626E+04	0.15900E-01	0.00000E+00	NORMAL	-0.13432E+03	0.12386E+04	0.45839E+03	0.00000E+00
44	LF-TB-TQ	0.97352E+03	0.18200E-01	0.00000E+00	NORMAL	0.35028E+03	0.29032E+03	0.33292E+03	0.00000E+00
45	HO-TB-TQ	0.44605E+04	0.10800E-01	0.00000E+00	NORMAL	-0.24908E+03	0.23122E+04	0.27374E+04	-0.34008E+03
46	HF-TB-TQ	0.95479E+04	0.14200E-01	0.00000E+00	NORMAL	-0.93543E+02	0.54258E+04	0.42156E+04	0.00000E+00
47	LO-TB-FL	0.17602E+03	0.99000E-02	0.00000E+00	NORMAL	0.34972E+02	0.17332E+03	-0.38821E+02	0.65423E+01
48	LF-TB-FL	0.26343E+02	0.17500E-01	0.00000E+00	NORMAL	0.10865E+02	0.31578E+01	0.12321E+02	0.00000E+00
49	HO-TB-FL	0.59921E+02	0.10100E-01	0.00000E+00	NORMAL	-0.16929E+01	0.49960E+02	0.11654E+02	0.00000E+00
50	HF-TB-FL	0.16065E+03	0.10700E-01	0.00000E+00	NORMAL	-0.12655E+02	0.14826E+03	0.16415E+02	0.86282E+01
51	LO-TB-PI	0.39407E+04	0.90000E-02	0.00000E+00	NORMAL	0.14676E+03	0.23734E+04	0.18122E+04	-0.39173E+03
52	LF-TB-PI	0.44928E+04	0.10500E-01	0.00000E+00	NORMAL	0.79100E+03	0.24002E+04	0.13015E+04	0.41025E+03
53	HO-TB-PI	0.50394E+04	0.88000E-02	0.00000E+00	NORMAL	-0.24624E+03	0.43569E+04	0.51853E+03	0.41025E+03
54	HF-TB-PI	0.49362E+04	0.95000E-02	0.00000E+00	NORMAL	-0.10228E+04	0.74803E+04	-0.34717E+04	0.19504E+04
55	LO-TB-TI	0.19024E+03	0.20000E-01	0.00000E+00	NORMAL	0.16515E+03	0.12327E+02	0.14901E+02	-0.21390E+01
56	LF-TB-TI	0.49091E+03	0.12100E-01	0.00000E+00	NORMAL	0.34906E+03	0.33392E+03	-0.19207E+03	0.00000E+00
57	HO-TB-TI	0.14290E+04	0.26600E-01	0.00000E+00	NORMAL	0.53754E+03	0.69823E+03	0.19324E+03	0.00000E+00
58	HF-TB-TI	0.18973E+04	0.18600E-01	0.00000E+00	NORMAL	0.16639E+04	-0.27369E+03	0.50710E+03	0.00000E+00
59	LO-TB-PO	0.41335E+03	0.20800E-01	0.00000E+00	NORMAL	0.10909E+03	0.35361E+03	-0.69451E+01	-0.42401E+02
60	LF-TB-PO	0.34038E+04	0.76000E-02	0.00000E+00	NORMAL	0.28588E+03	0.27154E+04	0.40252E+03	0.00000E+00

Hit any key to continue
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LDEP-ID	LD-NAME	MEAN	COV	P3	DIST	NE-COEF1	NE-COEF2	NE-COEF3	NE-COEF4
61	HO-TB-PO	0.33262E+04	0.66000E-02	0.00000E+00	NORMAL	-0.14193E+03	0.36618E+04	-0.46887E+03	0.27518E+03
62	HF-TB-PO	0.34781E+04	0.67000E-02	0.00000E+00	NORMAL	-0.26661E+03	0.42106E+04	-0.97850E+03	0.51460E+03

TABLE B.3

INFC: INFLUENCE COEFFICIENTS AND GAINS DATABASE (SAMPLE, GROUP #1)

LDEP-ID	LIDP-ID	INFL-C1	INFL-C2	INFL-C3	INFL-C4
1	1	-0.27814E-01	0.43114E+00	-0.13497E+00	0.00000E+00
1	2	0.65117E-05	0.00000E+00	0.00000E+00	0.00000E+00
1	3	-0.14568E-02	0.00000E+00	0.00000E+00	0.00000E+00
1	4	-0.22914E-01	0.47516E-01	0.58451E-01	0.00000E+00
1	5	0.26950E-01	-0.60455E-01	0.00000E+00	0.00000E+00
1	6	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
1	7	-0.56472E-02	0.00000E+00	0.00000E+00	0.00000E+00
1	8	0.39749E-04	-0.77072E-04	0.00000E+00	0.00000E+00
1	9	0.16538E-02	0.28197E-01	0.00000E+00	0.00000E+00
1	10	0.81111E-01	-0.15953E+00	0.11391E+00	0.00000E+00
1	11	0.24479E-01	0.25786E-01	-0.24154E-01	0.00000E+00
1	12	0.83620E-02	0.00000E+00	0.00000E+00	0.00000E+00
1	13	-0.51053E-02	0.00000E+00	0.00000E+00	0.00000E+00
1	14	-0.74828E-04	0.00000E+00	0.00000E+00	0.00000E+00
1	15	-0.23868E+00	-0.33378E+00	0.00000E+00	0.00000E+00
1	16	-0.32305E-03	0.00000E+00	0.00000E+00	0.00000E+00
1	17	-0.38733E-02	0.33192E-02	-0.12312E-02	0.00000E+00
1	18	0.29213E-01	0.70875E-01	0.00000E+00	0.00000E+00
1	19	-0.10802E+00	-0.14021E-01	0.00000E+00	0.00000E+00
1	20	0.39947E-04	-0.75710E-04	0.00000E+00	0.00000E+00

Hit any key to continue

GAIN65	GAIN90	GAIN100	GAIN104
0.39080E-03	0.50176E-03	0.53670E-03	0.54917E-03
0.16865E-05	0.16865E-05	0.16865E-05	0.16865E-05
-0.47636E-03	-0.47636E-03	-0.47636E-03	-0.47636E-03
0.52268E-03	0.10751E-02	0.13289E-02	0.14356E-02
-0.13581E-03	-0.30206E-03	-0.36856E-03	-0.39516E-03
0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
-0.56473E-04	-0.56473E-04	-0.56473E-04	-0.56473E-04
-0.10348E-06	-0.29616E-06	-0.37323E-06	-0.40406E-06
0.19982E-03	0.27031E-03	0.29851E-03	0.30979E-03
0.25540E-04	0.29795E-04	0.35484E-04	0.38398E-04
0.19862E-02	0.17998E-02	0.16711E-02	0.16110E-02
0.53517E-03	0.53517E-03	0.53517E-03	0.53517E-03
-0.44927E-03	-0.44927E-03	-0.44927E-03	-0.44927E-03
-0.74828E-06	-0.74828E-06	-0.74828E-06	-0.74828E-06
-0.45564E-02	-0.53908E-02	-0.57246E-02	-0.58581E-02
-0.32305E-05	-0.32305E-05	-0.32305E-05	-0.32305E-05
-0.22360E-04	-0.18833E-04	-0.17853E-04	-0.17530E-04
0.11292E-02	0.13550E-02	0.15013E-02	0.15438E-02
-0.12945E-02	-0.15223E-02	-0.16135E-02	-0.16499E-02
-0.92640E-08	-0.28192E-07	-0.35763E-07	-0.38791E-07

Hit any key to continue

125

LDEP-ID	LIDP-ID	INFL-C1	INFL-C2	INFL-C3	INFL-C4	GAIN65	GAIN90	GAIN100	GAIN104
1	21	-0.78040E-01	-0.43308E+00	0.22515E+00	0.00000E+00	-0.26442E-03	-0.28544E-03	-0.28597E-03	-0.28492E-03
1	22	0.53094E-02	-0.14335E-01	0.63777E-02	0.00000E+00	-0.13139E-05	-0.24263E-05	-0.26481E-05	-0.27011E-05
1	23	-0.35920E-02	0.46096E-02	-0.33199E-02	0.00000E+00	-0.19984E-05	-0.21324E-05	-0.23023E-05	-0.23888E-05
2	1	-0.70750E+00	0.11442E+01	-0.77700E+00	0.00000E+00	-0.50414E-03	-0.61423E-03	-0.68066E-03	-0.71593E-03
2	2	0.23386E-04	0.00000E+00	0.00000E+00	0.00000E+00	0.60570E-05	0.60570E-05	0.60570E-05	0.60570E-05
2	3	-0.10823E-02	0.10242E-01	-0.67591E-02	0.00000E+00	0.83924E-03	0.87009E-03	0.78507E-03	0.73868E-03
2	4	-0.36225E-01	0.29168E+00	-0.11614E+00	0.00000E+00	0.16687E-02	0.21154E-02	0.22290E-02	0.22641E-02
2	5	-0.23446E+00	0.67328E+00	-0.22132E+00	0.00000E+00	0.12062E-02	0.21144E-02	0.23924E-02	0.24900E-02
2	6	0.59669E-02	-0.20774E-01	0.38678E-01	0.00000E+00	0.80052E-04	0.18599E-03	0.23871E-03	0.26196E-03
2	7	0.17321E-01	-0.11092E+00	0.43112E-01	0.00000E+00	-0.36559E-03	-0.47582E-03	-0.50482E-03	-0.51401E-03
2	8	-0.43625E-04	0.41073E-03	0.00000E+00	0.00000E+00	0.22335E-05	0.32603E-05	0.36711E-05	0.38354E-05
2	9	0.28057E-02	-0.79636E-02	0.30278E-02	0.00000E+00	-0.10914E-04	-0.19090E-04	-0.21301E-04	-0.22016E-04
2	10	-0.68844E-03	0.00000E+00	0.00000E+00	0.00000E+00	-0.68844E-06	-0.68844E-06	-0.68844E-06	-0.68844E-06
2	11	0.54763E-02	-0.32821E-02	0.29893E-02	0.00000E+00	0.29478E-03	0.31640E-03	0.33174E-03	0.33895E-03
2	12	-0.10445E-01	0.10481E-01	0.30273E-02	0.00000E+00	0.58610E-03	0.15046E-02	0.19398E-02	0.21247E-02
2	13	0.19591E-01	-0.50181E-01	0.37758E-01	0.00000E+00	0.25752E-03	0.44108E-03	0.63079E-03	0.72529E-03
2	14	0.54940E+00	-0.51475E+00	0.00000E+00	0.00000E+00	0.21481E-02	0.86123E-03	0.34648E-03	0.14058E-03
2	15	0.82966E-01	0.28195E-01	0.00000E+00	0.00000E+00	0.10129E-02	0.10834E-02	0.11116E-02	0.11229E-02
2	16	-0.15142E-04	0.00000E+00	0.00000E+00	0.00000E+00	-0.15142E-06	-0.15142E-06	-0.15142E-06	-0.15142E-06
2	17	-0.57622E-02	0.85120E-02	-0.40969E-02	0.00000E+00	-0.19604E-04	-0.14200E-04	-0.13472E-04	-0.13410E-04

Hit any key to continue

LDEP-ID	LIDP-ID	INFL-C1	INFL-C2	INFL-C3	INFL-C4	GAIN65	GAIN90	GAIN100	GAIN104
2	18	-0.79356E-02	0.32249E-01	0.00000E+00	0.00000E+00	0.19539E-03	0.31632E-03	0.36470E-03	0.38405E-03
2	19	0.15329E-01	-0.63553E-01	0.00000E+00	0.00000E+00	-0.16878E-03	-0.27203E-03	-0.31332E-03	-0.32984E-03
2	20	0.22903E-02	-0.58536E-02	0.41143E-02	0.00000E+00	0.22381E-06	0.35471E-06	0.55108E-06	0.65267E-06
2	21	0.10922E+00	0.16862E+00	-0.11706E+00	0.00000E+00	0.16937E-03	0.16616E-03	0.16079E-03	0.15798E-03
2	22	0.67418E-01	-0.81388E-01	0.56516E-01	0.00000E+00	0.38394E-04	0.39947E-04	0.42546E-04	0.43902E-04
2	23	-0.12710E-03	-0.14475E-02	0.00000E+00	0.00000E+00	-0.10680E-05	-0.14298E-05	-0.15746E-05	-0.16325E-05
3	1	0.68457E-01	0.18794E+00	0.00000E+00	0.00000E+00	0.38124E-03	0.47521E-03	0.51280E-03	0.52783E-03
3	2	-0.10704E-01	0.96549E-02	-0.50301E-02	0.00000E+00	-0.16974E-02	-0.15771E-02	-0.15746E-02	-0.15808E-02
3	3	-0.18513E-02	0.00000E+00	0.00000E+00	0.00000E+00	-0.60538E-03	-0.60538E-03	-0.60538E-03	-0.60538E-03
3	4	0.99277E+00	0.65602E-02	-0.14298E-01	0.00000E+00	-0.15586E-01	0.15794E-01	0.15761E-01	0.15746E-01
3	5	0.51484E-01	-0.27705E+00	0.11898E+00	0.00000E+00	-0.86163E-03	-0.11164E-02	-0.11725E-02	-0.11876E-02
3	6	0.11705E+00	-0.30573E+00	0.00000E+00	0.00000E+00	-0.81672E-03	-0.15810E-02	-0.18868E-02	-0.20091E-02
3	7	-0.80165E-02	0.17514E-01	0.00000E+00	0.00000E+00	0.33675E-04	0.77460E-04	0.94974E-04	0.10198E-03
3	8	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
3	9	0.12616E-01	0.00000E+00	0.00000E+00	0.00000E+00	0.12616E-03	0.12616E-03	0.12616E-03	0.12616E-03
3	10	0.37986E-04	0.19009E-03	0.00000E+00	0.00000E+00	-0.85573E-07	-0.13310E-06	-0.15210E-06	-0.15971E-06
3	11	0.29612E+00	-0.81485E-01	0.87444E-01	0.00000E+00	0.15562E-01	0.14258E-01	0.13737E-01	0.13528E-01
3	12	0.58834E-01	-0.12894E+00	0.85683E-01	0.00000E+00	0.76589E-03	0.87144E-03	0.11095E-02	0.12361E-02
3	13	-0.28219E+00	-0.26112E+00	0.00000E+00	0.00000E+00	-0.36583E-01	-0.39406E-01	-0.40271E-01	-0.40575E-01
3	14	-0.80618E-03	0.00000E+00	0.00000E+00	0.00000E+00	-0.80618E-05	-0.80618E-05	-0.80618E-05	-0.80618E-05

Hit any key to continue

126

LDEP-ID	LIDP-ID	INFL-C1	INFL-C2	INFL-C3	INFL-C4	GAIN65	GAIN90	GAIN100	GAIN104
3	15	0.34584E+00	-0.24002E+01	0.27821E+01	0.00000E+00	-0.38873E-03	0.43914E-02	0.72772E-02	0.85873E-02
3	16	-0.16066E+03	0.00000E+00	0.00000E+00	0.00000E+00	-0.16066E-05	-0.16066E-05	-0.16066E-05	-0.16066E-05
3	17	0.21429E-03	0.00000E+00	0.00000E+00	0.00000E+00	0.21429E-05	0.21429E-05	0.21429E-05	0.21429E-05
3	18	0.55468E-02	0.13787E+00	-0.36596E-01	0.00000E+00	0.11955E-02	0.14999E-02	0.16024E-02	0.16403E-02
3	19	0.80333E-03	-0.29378E-02	0.41643E-02	0.00000E+00	0.42456E-05	0.99606E-05	0.13194E-04	0.14639E-04
3	20	0.11531E-01	-0.32619E-01	0.14282E-01	0.00000E+00	-0.36377E-05	0.62582E-05	-0.68066E-05	-0.69460E-05
3	21	-0.14556E-02	0.00000E+00	0.00000E+00	0.00000E+00	-0.14556E-05	-0.14556E-05	-0.14556E-05	-0.14556E-05
3	22	0.41060E-03	0.00000E+00	0.00000E+00	0.00000E+00	0.41060E-06	0.41060E-06	0.41060E-06	0.41060E-06
3	23	-0.13397E-01	0.00000E+00	0.00000E+00	0.00000E+00	-0.13397E-04	-0.13397E-04	-0.13397E-04	-0.13397E-04
4	1	-0.10501E+01	0.11774E+01	-0.60162E+00	0.00000E+00	-0.10780E-02	0.95561E-03	-0.94875E-03	-0.95275E-03
4	2	-0.11581E-01	0.11823E-01	-0.62736E-02	0.00000E+00	-0.16955E-02	0.15596E-02	-0.15621E-02	-0.15722E-02
4	3	0.30526E+00	0.38266E+00	0.28524E+00	0.00000E+00	0.57892E-01	0.62752E-01	0.67960E-01	0.70566E-01
4	4	0.98463E+00	0.52394E-01	-0.16327E-01	0.00000E+00	0.16189E-01	0.16297E-01	0.16331E-01	0.16343E-01
4	5	-0.16258E+00	0.75694E+00	-0.42207E+00	0.00000E+00	0.16621E-02	0.19446E-02	0.18951E-02	0.18493E-02
4	6	0.32129E-01	-0.73425E-01	0.12076E+00	0.00000E+00	0.35425E-03	0.63864E-03	0.79466E-03	0.86384E-03
4	7	-0.25863E-01	0.64959E-01	0.86592E-01	0.00000E+00	0.52945E-03	0.10274E-02	0.12569E-02	0.13535E-02
4	8	0.44275E-03	-0.89531E-03	0.00000E+00	0.00000E+00	-0.13920E-05	-0.36302E-05	-0.45255E-05	-0.48836E-05
4	9	-0.79141E-03	0.25753E-02	-0.66043E-03	0.00000E+00	0.60551E-05	0.99142E-05	0.11235E-04	0.11726E-04
4	10	0.12615E-02	0.00000E+00	0.00000E+00	0.00000E+00	0.12615E-05	0.12615E-05	0.12615E-05	0.12615E-05
4	11	0.95561E-03	-0.63542E-01	0.38902E-01	0.00000E+00	-0.15303E-02	0.15822E-02	-0.15158E-02	-0.14753E-02

LDEP-ID	LIDP-ID	INFL-C1	INFL-C2	INFL-C3	INFL-C4	GAIN65	GAIN90	GAIN100	GAIN104
4	12	0.20614E-05	-0.14343E-02	0.34756E-03	0.00000E+00	-0.50137E-04	-0.64466E-04	-0.69419E-04	-0.71276E-04
4	13	-0.13028E-04	0.66785E-04	0.00000E+00	0.00000E+00	0.26736E-05	0.41429E-05	0.47306E-05	0.49657E-05
4	14	0.82796E-02	0.95136E-03	-0.53166E-01	0.00000E+00	-0.13565E-03	-0.33929E-03	-0.43935E-03	-0.48236E-03
4	15	-0.47086E+01	0.83353E-01	-0.55375E-01	0.00000E+00	-0.16302E-01	-0.16922E-01	-0.19107E-01	-0.20292E-01
4	16	-0.33740E+00	0.00000E+00	0.00000E+00	0.00000E+00	-0.33740E-02	-0.33740E-02	-0.33740E-02	-0.33740E-02
4	17	-0.76319E-03	0.00000E+00	0.00000E+00	0.00000E+00	-0.76319E-05	-0.76319E-05	-0.76319E-05	-0.76319E-05
4	18	-0.17434E-01	0.50127E-01	-0.13107E-01	0.00000E+00	0.14417E-03	0.25597E-03	0.29381E-03	0.30784E-03
4	19	-0.10966E+00	0.38727E+00	-0.17148E+00	0.00000E+00	0.45253E-03	0.64992E-03	0.68986E-03	0.69960E-03
4	20	-0.10278E-01	0.36234E-01	-0.17128E-01	0.00000E+00	0.60375E-05	0.84591E-05	0.88282E-05	0.88799E-05
4	21	0.63799E-02	0.31966E-02	0.00000E+00	0.00000E+00	0.84577E-05	0.92569E-05	0.95765E-05	0.97044E-05
4	22	0.11667E-02	-0.12175E-02	0.00000E+00	0.00000E+00	0.37539E-06	0.71027E-07	-0.50720E-07	-0.99419E-07
4	23	0.83379E-01	-0.21687E+00	0.85345E-01	0.00000E+00	-0.21029E-04	-0.42175E-04	-0.47647E-04	-0.49357E-04

127

TABLE B.4

LTBC: TURBINE BLADE COMPONENT LOAD DATABASE

TB-C-ID	TB-LD-ID	TB-LD-NA	LD-TYPE	LDEP1-ID	LDEP2-ID	SC-COEF	TBC-GRPN
1	1	HF-CFG	POINT	2	0	0.10000E+01	SCF1
1	2	HF-MP-T1	POINT	46	0	0.11623E-01	SCF1
1	3	HF-MP-T2	POINT	46	0	0.19194E-01	SCF1
1	4	HF-MP-A1	POINT	54	62	0.98384E-01	SCF1
1	5	HF-MP-A2	POINT	54	62	0.78707E-01	SCF1
1	6	HF-T-T1	DIST	46	0	0.11623E-01	SCF1
1	7	HF-T-T2	DIST	46	0	0.19194E-01	SCF1
1	8	HF-T-A1	DIST	54	62	0.98384E-01	SCF1
1	9	HF-T-A2	DIST	54	62	0.78707E-01	SCF1
1	10	HF-MN-T1	DIST	46	0	0.11623E-01	SCF1
1	11	HF-MN-T2	DIST	46	0	0.19194E-01	SCF1
1	12	HF-MN-A1	DIST	54	62	0.98384E-01	SCF1
1	13	HF-MN-A2	DIST	54	62	0.78707E-01	SCF1
1	14	HF-H-T1	DIST	46	0	0.11623E-01	SCF1
1	15	HF-H-T2	DIST	46	0	0.19194E-01	SCF1
1	16	HF-H-A1	DIST	54	62	0.98384E-01	SCF1
1	17	HF-H-A2	DIST	54	62	0.78707E-01	SCF1
1	18	HF-T-DP	NODES	19	46	0.00000E+00	SCF1
1	19	HF-MN-DP	NODES	19	46	0.00000E+00	SCF1
1	20	HF-H-DP	NODES	19	46	0.00000E+00	SCF1
1	21	HF-DYN-P	POINT	2	0	0.00000E+00	SCF1

TABLE B.5

DFAT: FLIGHT AND TEST
DUTY-CYCLE-DATA DATABASE

DCD-ID	LIDP-ID	ENGINE	MISSION	DCD-GRPN
STS61-A	0	SSME	FLIGHT	PWR1
STS61-A	1	SSME	FLIGHT	MXR1
STS61-A	2	SSME	FLIGHT	PIF1
STS61-A	3	SSME	FLIGHT	PIO1
STS61-A	4	SSME	FLIGHT	TIF1
STS61-A	5	SSME	FLIGHT	TIO1
902-384	0	SSME	TEST	PWR3
902-384	1	SSME	TEST	MXR3
902-384	2	SSME	TEST	PIF3
902-384	3	SSME	TEST	PIO3
902-384	4	SSME	TEST	TIF3
902-384	5	SSME	TEST	TIO3
902-387	0	SSME	TEST	PWR4
902-387	1	SSME	TEST	MXR4
902-387	2	SSME	TEST	PIF4
902-387	3	SSME	TEST	PIO4
902-387	4	SSME	TEST	TIF4
902-387	5	SSME	TEST	TIO4
750-262	0	SSME	TEST	PWR5
750-262	1	SSME	TEST	MXR5

Hit any key to continue

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DCD-ID	LIDP-ID	ENGINE	MISSION	DCD-GRPN
750-262	2	SSME	TEST	PIF5
750-262	3	SSME	TEST	PIO5
750-262	4	SSME	TEST	TIF5
750-262	5	SSME	TEST	TIO5
901-495	0	SSME	TEST	PWR6
901-495	1	SSME	TEST	MXR6
901-495	2	SSME	TEST	PIF6
901-495	3	SSME	TEST	PIO6
901-495	4	SSME	TEST	TIF6
901-495	5	SSME	TEST	TIO6
901-491	0	SSME	TEST	PWR7
901-491	1	SSME	TEST	MXR7
901-491	2	SSME	TEST	PIF7
901-491	3	SSME	TEST	PIO7
901-491	4	SSME	TEST	TIF7
901-491	5	SSME	TEST	TIO7

DATABASE COMMANDS AND ROUTINES DESCRIPTION

Available Database Commands:

?DBCR : Create a database table
?DBBK : Build a database key file
?DBDF : Display field and key names
?DBSL : Select database records
?DBDL : Delete database records
?DBUP : Update (add) database records
?DBRD : Open a database file and read its data dictionary
?DBSV : Save a updated database table
?DBLT : List a complete database table
?DBLK : List a complete database key file
?DBCF : Create fields for a database table
?INLD : Build a load ID and properties database
?INFL : Build an influence coefficients and gains database

DBMS Routines:

DBMS   : Database System driver
DBCRTB : ?DBCR command, create a database table
DBBUKE : ?DBBK command, building a key file
DBDPKF : ?DBDF command, display field and key names
DBRDDC : ?DBRD command, open a Database file and read a Database
         table dictionary
DBSLRC : ?DBSL command, select, retrieve and display records of a
         Database table

```
DBUPTB : ?DBUP command, update (add) new records to a Database table
DBDLRC : ?DBDL command, delete records from a Database table
DBSVTB : ?DBSV command, save a Database table to a Database file
DBLSTB : ?DBLT command, list data on a Database table
DBLSKF : ?DBLK command, list key data of a Database table
DBGEIN : get record indices for the requested records
DBWRFD : display selected records on CRT
DBWRRC : write a retrieved record to CRT
PRPAGE : print a page of data on CRT
DBRDKD : read field and key descriptions from terminal input
DBRDDA : read Database table input from terminal
DBRDFD : read a field data from terminal input
SORKEY : set up a multiple sort procedure and call SHLSO2
SHLSO2 : a shell sort routine for a two-column-array
DBSWIT : switch (substitute) row(index1) by row(index2)
```

LDEXPT Rule Modules and Routine Descriptions

Rule module for duty-cycle-data base:

If   the flight or test data ID is XXXXXXX and
     the independent load ID is N
then the engine type for this data is YYYY,
     the mission history profile type is ZZZZZ,
     the data is stored in the duty-cycle-data base file with
     group name AAAA.

Rule module for the Quick Look Model:

If   the dependent load ID is N and
     the user requests a quick look model calculation
then the expert system will either request user to select the
     independent loads manually or the expert system will select
     them,
     retrieve influence coefficient set and
     perform the quick look model calculation.

Rule module for turbine blade load scaling model

a) If   the turbine blade component ID of interest is M and
        the turbine blade component load ID is N
   then the turbine blade component load name is AAAAAAA,
        its load type is.TYPE-X,
        the dependent loads needed for the scaling model are load ID1
        and load ID2 (if required),
        the scaling model coefficient is NNNN or
        the coefficients are stored in a duty-cycle-data base file
        with group name BBBB (if more than one coefficient is
        required).

b) If   a turbine blade load calculation is requested and
        the turbine blade component and load are M and N
    then the expert system will generate an input file for an ANLOAD
        calculation which includes the following information:
        the independent and dependent loads required and
        their relevant load parameters and
        the influence coefficient sets and
        the duty-cycle-data for dependent loads if necessary and
        computational parameters such as number of bins, time slices
        etc. by prompting the user.

c) If   the turbine blade component and load are M and N and
        the user requests a simple turbine blade scaling model
        calculation
    then the expert system will retrieve the default dependent load
        information and scaling coefficient(s) and
        perform a turbine blade scaling model calculation.

The rule module routines:

RBIDPL : rule module for retrieving independent load
information and selecting independent loads for users
based on the gain database

RBDEPL : retrieving dependent load information manually or by
the expert system with the help of the simple working
memory model

RBTBCL : retrieving turbine blade component load information
and scaling model information

RBQLM : the quick look model, calculating dependent loads
assuming all loads are normally distributed

RBSICM : the deterministic influence coefficient model,
calculating point values for dependent loads using
influence coefficients

RBDRIV : the new rule base driver routine

RBICGN : retrieving the influence coefficient set and the gain
database

RBSSM : rule module for performing simple scaling model
calculation using default dependent load values

RBDCD : retrieving flight or test duty-cycle-data files

RBTBIN : preparing an ANLOAD input file for a full blown ANLOAD
calculation

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11. SUPPLEMENTARY NOTES

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12a. DISTRIBUTION/AVAILABILITY STATEMENT

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13. ABSTRACT (Maximum 200 words)

The objective of this program is to develop generic load models with multiple levels of progressive sophistication to simulate the composite (combined) load spectra that are induced in space propulsion system components, representative of Space Shuttle Main Engines (SSME), such as transfer ducts, turbine blades, and liquid oxygen (LOX) posts and system ducting. These models will be developed using two independent approaches. The first approach will consist of using state-of-the-art probabilistic methods to describe the individual loading conditions and combinations of these loading conditions to synthesize the composite load spectra simulation. The methodology required to combine the various individual load simulation models (hot-gas dynamic, vibrations, instantaneous position, centrifugal field, etc.) into composite load spectra simulation models will be developed under this program. A computer code incorporating the various individual and composite load spectra models will be developed to construct the specific load model desired. The second approach, which is covered under the unfunded options portion of the contract, will consist of developing coupled models for composite load spectra simulation which combine the (deterministic) models for composite load dynamic, acoustic, high-pressure and high rotational speed, etc., load simulation using statistically varying coefficients. These coefficients will then be determined using advanced probabilistic simulation methods with and without strategically selected experimental data. The first year's effort completed sufficient subsets for each task—probabilistic models and code development of turbine blade loads to have an operational code for evaluating the overall approach. The second year effort has been to continue the overall probabilistic load development work, extend the effort into a more generic approach to the loads, assemble information on the transfer ducts and significantly improve the expert system approach to interface with the user.

14. SUBJECT TERMS

Load models; Turbine blades; Transfer ducts; Liquid-oxygen; Posts; System ducting; Probabilistic methods; Hot-gas dynamics; Vibrations; Expert systems; Computer codes

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